Biomonitoring using diatoms and paleolimnology in the Western Great Lakes National Parks

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CONTENTS

ANNUAL SUMMARY

Our 2006-2007 monitoring year activities targeted Voyageurs National Park (VOYA), Indiana Dunes National Lakeshore (INDU), and Mississippi National River and Recreation Area (MISS). Water quality monitoring and surface sediment collection were completed on 27 lakes although several lakes were removed from the data set because of poor sediment deposition (MISS RM852, INDU George). Surface sediment samples from 15 of the lakes were analyzed for diatom remains. Lakes that were not analyzed in this field year will be analyzed during the 2008-2009 field year. Three VOYA lakes were selected for long core collection. Ek Lake, Peary Lake, and Cruiser Lake in VOYA were cored in July 2006.

Water quality analysis is complete and data for field years 2005, 2006, and 2007 have been summarized. A principal components analysis showed that water quality in lakes was strongly separated by park units with VOYA lakes, MISS lakes, and INDU (Long) separated from a grouping of PIRO and SLBE lakes. Two major environmental gradients were apparent. The strongest gradient was along the pH, alkalinity, conductivity, sulfate, Mg, Ca vectors and provided strong separation of the VOYA lakes from PIRO/SLBE lakes. The INDU and MISS lakes were separated along the nutrient/productivity gradient, where Secchi, TP, TN, Chl a and NO_3-NO_2 were strongly correlated. Among this set of lakes, the MISS lakes were outliers and when removed from the analysis, weakened the nutrient/productivity gradient.

Diatoms preserved in surface sediment samples in 2006 were extremely diverse with over 500 diatom taxa recorded. The VOYA sediments were dominated by the planktonic or softwater taxa *Cyclotella ocellata*, *Discostella stelligera*, *Asterionella formosa*, *Aulacoseira tenella*, *A. ambigua*, and *Eunotia zasuminensis*. The MISS and INDU samples were dominated by taxa indicative of higher productivity including the planktonic taxa *Cyclotella meneghiniana* and *Stephanodiscus minutulus* and abundant monoraphid and araphid species. A canonical correspondance analysis (CCA) of the pooled 2005 and 2006 surface sediments and environmental data showed that four environmental gradients accounted for significant and independent variation in the species abundance and distribution: total nitrogen, ammonium, calcium and specific conductivity.

The three long cores recovered from VOYA lakes were analyzed for Pb-210 inventory to create a date-depth model and sedimentation rates for each core; loss on ignition to determine organic, carbonate, and inorganic content; biogenic silica as a proxy for algal production; and subfossil diatoms, our target indicator organisms. Two historical responses were common among all cores. First, all lakes showed increased sedimentation rates in the early 20th century, probably in response to initial logging and settlement in the region. Second, all lakes had their greatest change in diatom communities in the late 19th century concurrent with initial Euroamerican interest and activity in the region. Surprisingly, there was much less change in diatom communities after initial logging and settlement. In a separate study, changes in diatom communities in VOYA's large lakes could be linked to land use and climate variation; these drivers are apparently far less influential in VOYA's smaller inland lakes.

Last, historical diatom communities in VOYA, PIRO, and SLBE cores were passively plotted on the species-environment ordination of the GLKN lakes to explore what environmental factors may have been driving changes in historical diatom communities. Results indicate that, in the context of the range of lake types and diatom communities in all GLKN lakes sampled to date, most of the cored lakes have had only small changes in their diatom communities in the last 200 years. In contrast, Manitou Lake at SLBE had dramatic changes in both diatom communities and biogeochemical proxies. Changes in the historical Manitou diatom communities suggest that declining nutrient levels and shifts along the conductivity, alkalinity, pH axes may be factors contributing to ecological change in this lake.

Key words: biomonitoring, inventory and monitoring, water quality, diatoms, landuse, climate change, paleolimnology, geochemistry

Abbreviations: PIRO-Pictured Rocks National Lakeshore, SLBE-Sleeping Bear Dunes National Lakeshore, VOYA-Voyageurs National Park, MISS-Mississippi National River and Recreation Area, INDU-Indiana Dunes National Lakeshore, GPS-global positioning system, UTM-universal transverse meridian, CCA-canonical correspondence analysis, PCA-principal components analysis, CA-correspondence analysis, DCA-detrended correspondence analysis, WQ-water quality, TP-total phosphorus, TN-total nitrogen, Mg-magnesium, Ca-calcium, Chl a-chlorophyll a, TKN-total Kjeldahl nitrogen, DOC-dissolved organic carbon, K-potassium, Cl-chloride, EC25-specific conductance normalized to 25°C.

INTRODUCTION

In Great Lakes Network (GLKN) park units, climate change, environmental contaminants, exotics, and land and resource uses including shoreline and urban development, recreation, water level management, logging, and agriculture have raised concerns about the state of the parks' resources and how to best manage them in a future certain to bring change. In this report, we summarize the second year of a strategy to integrate the use of paleolimnological techniques and diatom analysis in an inventory and monitoring framework. Results of this and subsequent reports will provide a management foundation by determining the natural variability or reference condition of national park lakes by reconstructing a detailed history of lake response to ecological changes that have occurred in and around the lakes during the last 200 years. Because lake-sediment records integrate across both spatial and temporal scales, research results will be further used as a biomonitoring strategy by revisiting lakes on regular intervals (3-5 years) to quantify modern environmental conditions relative to historical conditions, to detect early ecological change and recent trends, and to evaluate success of management actions.

METHODS

Water quality sampling: Sampling for physical and water chemistry parameters took place three times on each lake during field year 2006 in VOYA, INDU, and eight times on river sites at MISS during field year 2006 (Elias and Sieracki 2007, Elias and VanderMeulen 2008). Twenty-seven lakes were selected with 22 in VOYA, three along MISS, and two in INDU (Elias et al. 2008, Ramstack et al. 2008).   Methods, initial compilation of data, and QC have been summarized (Elias and VanderMeulen 2008). All WQ data for this report have been expressed as mean values of the ice-free season.

Surface sediment and long core collection: Lakes were selected for coring using a random process after pre-screening lakes using criteria that included lake depth (shallow lakes deleted), knowledge of lake conditions (lakes known to lack diatom preservation removed), and park priorities (index lakes). A line-operated gravity corer (design by Harold Wiegner, Harold.Wiegner@state.mn.us) was used to collect the upper 0-1 cm and 1-2 cm of sediment at the same site that water quality measures were taken. These sediments represent a spatially and temporally integrated assessment of biological remains and lake conditions during the past 1-3 years. Collection sites were precisely located by GPS to allow resampling in the same location in subsequent years; sampling sites always target central depositional basins in each lake (Ramstack et al. 2008).

Piston coring locations targeted central depositional basins in each lake, usually the same location where water quality measures and surface sediments were taken. In Cruiser Lake the more easterly basin was cored rather than the westerly basin, which was used for WQ analysis; the latter is too deep for rigid drive rod coring techniques from an anchored boat. Long cores were taken from an anchored boat using piston-coring methods that recover the very loose uncompacted sediment surface without disturbance (Wright 1991). Coring locations were recorded using GPS. Sediment cores were extruded vertically from the coring tube in the field at

1-cm increments to 60-85 cm core depth and placed in polypropylene jars; the remainder of the core was capped. Cores and sectioned material were transported to 4° C laboratory storage for further processing.

Sediment subsampling and freeze-drying: Sediment samples were homogenized and subsampled for loss-on-ignition and/or diatom analyses. The remaining sediments were freeze-dried within the sample jars for ^{210}Pb analysis and archived at the St. Croix Watershed Research Station (Science Museum of Minnesota).

Loss-on-ignition: Dry-density (dry mass per volume of fresh sediment), water content, organic content, and carbonate content of sediments were determined by standard loss-on-ignition techniques (Dean 1974). In short, weighed sediment subsamples were dried at 105°C for 24 hr to determine dry density, then heated at 550°C and 1000°C to determine organic and carbonate content from post-ignition weight loss, respectively.

Lead-210 dating of cores: Sediment cores were analyzed for ^{210}Pb activity to determine age and sediment accumulation rates for the past 150-200 years. Lead-210 activity was measured from its daughter product, ^{210}Po, which is considered to be in secular equilibrium with the parent isotope. Aliquots of freeze-dried sediment were spiked with a known quantity of ^{209}Po as an internal yield tracer and the isotopes distilled at 550°C after treatment with concentrated HCl. Polonium isotopes were then directly plated onto silver planchets from a 0.5 N HCl solution. Activity was measured for $1-3 \times 10^5$ s using an Ortec alpha spectrometry system. Supported ^{210}Pb was estimated by the mean activity in the lowest core samples and subtracted from upcore activity to calculate unsupported ^{210}Pb. Core dates and sedimentation rates were calculated using the constant rate of supply model (Appleby and Oldfield 1978). Dating and sedimentation errors represent first-order propagation of counting uncertainty (Binford 1990). Pre-1850 dates and sedimentation rates represent down-core extrapolations of mean dry-mass accumulation immediately pre-settlement.

Diatom analysis—surface sediments and long cores: Surface sediments and fifteen increments from each core were analyzed for diatom microfossils. Samples from cores were taken at approximately decadal intervals over the past 200 years to provide a chronology of environmental change following regional European settlement and a measure of reference or pre-settlement conditions. Diatoms and chrysophyte cysts were prepared by placing approximately 0.25 cm^3 of homogenized sediment in a 50 cm^3 polycarbonate centrifuge tube, adding 2-5 drops of 10% v/v HCl solution to dissolve carbonates. Organic material was subsequently oxidized by adding 10 ml of 30% hydrogen peroxide and heating for 3 hours in a 85°C water bath. After cooling the samples were rinsed with deionized water to remove oxidation biproducts. Aliquots of the remaining material, which contain the diatoms, were dried onto 22x22 mm #1 coverglasses, which were then permanently attached to microscope slides using Zrax mounting medium (Ramstack et al. 2008). Diatoms were identified along random transects to the lowest taxonomic level under 1250X magnification (full immersion optics of NA 1.4). A minimum of 400 valves was counted in each sample. Abundances are reported as percentage abundance relative to total diatom counts.

Biogenic silica—long cores: The same fifteen samples from each long core that were analyzed for diatoms were also analyzed for biogenic silica. Weighed subsamples (30 mg) from each primary core were digested for biogenic silica analysis using 40 mL of 1% (w/v) Na_2CO_3

solution heated at 85°C in a reciprocating water bath for five hours (DeMaster 1979, Conley and Schelske 2001). A 0.5 g aliquot of supernatant was removed from each sample at 3, 4, and 5 h. After cooling and neutralization with 4.5 g of 0.021N HCl solution, dissolved silica was measured colorimetrically on a Lachat QuikChem 8000 flow injection autoanalyzer as molybdate reactive silica (McKnight 1991).

Numerical analysis: A number of multivariate techniques were used to analyze environmental data, modern diatom communities, and historical diatom assemblages among GLKN lakes and sediment cores. Relationships among lakes and environmental variables were explored using Principal Components Analysis (PCA) performed on a correlation matrix of the 12 water quality variables using the software package R (Ihaka and Gentleman 1996) following scaling of all variables to zero mean and unit variance.

Relationships among diatom communities within a sediment core were explored using Principal Components Analysis, Correspondence Analysis, or Detrended Correspondence Analysis (depending on gradient length as determined by DCA). Core depths were plotted in ordinate space (by ^{210}Pb date) and their relationships and variability used to identify periods of change, sample groups, and ecological variability among core samples.

Relationships among environmental variables and species distributions for the 2005 and 2006 GLKN lakes were explored using canonical correspondence analysis (CCA), a multivariate ordination technique for direct gradient analysis (ter Braak and Prentice 1988) available in the software package R (Ihaka and Gentleman 1996). Species present at greater than 1% relative abundance in two or more surface sediment samples or at greater than 5% relative abundance in one sample were included in ordination analyses; the same selection criteria were used by Ramstack et al. (2003). Environmental variables were variously transformed (log, inverse, or no transformation) to approximate a normal distribution (Table 1). The distribution of species among samples was initially explored with detrended correspondence analysis (DCA) and correspondence analysis (CA), respectively, to determine gradient length and examine the variation in the species data. These preliminary analyses are the first step in developing a calibration or training set that will allow diatom communities in GLKN park lakes to be used to infer modern and historical water quality data. This training set will continue to be developed as additional GLKN lakes are added in subsequent field years. Downcore community data were passively plotted in the environmental-diatom CCA to identify ecological trajectories for each sediment core and along which environmental gradients the community may be changing.

Land-use history: A record of major land-use changes from VOYA has been assembled by Larry Kallemeyn and coauthors as part of a separate project (Edlund et al. 2008). Land-use histories will be compared with trophic reconstructions and diatom stratigraphic zones from the sediment cores to determine whether major changes in ecological conditions are temporally correlated with specific disturbances in the watershed.

RESULTS

WATER QUALITY

For analysis of relationships between diatoms and environmental parameters, annual data have been summarized as mean values across all annual sampling events (Table 2). The 2006 WQ data have also been tabulated with 2005 annual mean data from SLBE and PIRO (Table 2).

The initial exploration of WQ parameters for 2005 and 2006 was done using principal components analysis on 12 environmental variables. Lakes from INDU and MISS that did not produce good surface sediment samples for diatom analysis, and VOYA lakes that will be analyzed for diatoms in 2008 were not included in this year's analysis. The PCA was run twice, once with all lakes and then excluding the MISS (Coon Rapids and Spring Lake) sites. The MISS sites were slight outliers based on WQ alone but were extreme outliers in terms of diatom communities (see below). Regardless of PCA, there were distinct gradients along axes 1 and 2 (Figs. 1a, b). Alkalinity, pH, and specific conductance factors (pH, Alk, Ca, Mg, EC25, SO_4) comprised the primary gradient, whereas the secondary gradient was more closely aligned with productivity and minor ion factors (Chla, TN, TP, Secchi, K, Cl; Figs. 1a, b). Lakes were clearly grouped by park unit with VOYA lakes separated from SLBE, PIRO, INDU, and MISS lakes along axis 1, and lakes distributed among and within park units along axis 2 (Figs.1a, b).

SURFACE SEDIMENT

The upper 0-1 cm and 1-2 cm segments of a short sediment core were collected from 22 lakes in VOYA, three from MISS, and two from INDU. Collection sites, sampling dates, and GPS coordinates are summarized in Table 3.

SEDIMENT CORING

Sediment cores were collected from three target lakes in VOYA in 2006: Cruiser Lake, Ek Lake, and Peary Lake (Table 4). Cores ranged in length from 0.88 m to 1.35 m.

LEAD-210 CORE DATING AND CORE BIOGEOCHEMISTRY

The three long cores from VOYA were dated using downcore inventories of ^{210}Pb. All cores had monotonic declines in Pb-210 inventories and generated good date-depth models with sufficient pre- and post-European sediment records for our analytical needs. Loss-on-ignition (LOI) analysis was used to determine dry density and weight percent organic, carbonate, and inorganic matter from each core, and in conjunction with the dating model, was used to calculate sedimentation rates for each core. Lastly, biogenic silica was analyzed in the same 15 downcore depths used for diatom analysis as a proxy for paleoproductivity. Results of dating, LOI, and biogenic silica analyses are presented for individual cores.

Cruiser Lake (VOYA)—Cruiser Lake sediments have a steady decline in ^{210}Pb inventory and reach supported levels at 15 cm depth (Fig. 2). The Euroamerican settlement date (1870s) is

located at approximately 11 cm core depth. Sedimentation rates increase in Cruiser Lake after 1920 to modern levels that are potentially four- to five-fold higher than background conditions (Fig. 3). It is difficult to conceive how sedimentation rates could change and continue to increase in this isolated lake, because logging and fire activity peaked on the peninsula in the early 20th century. Alternatively, the basin where the core was collected was small and steep-sided, thus the potential for a change in sediment focusing exists.

Organic, carbonate and inorganic content of the Cruiser Lake core varied little in the last 250 years. Sediments are dominated by inorganic content at about 60% by weight, and secondarily by organic content (~30% by weight; Fig. 4). As might be expected on the Voyageurs peninsula, the carbonate content in the sediments is very low (Fig. 4). Biogenic silica has declined slightly upcore from a long-term average of about 20% by weight to about 18% at the core top (Fig. 5). When expressed as flux, biogenic silica deposition has increased approximately four-fold between the 1920s and the top of the core.

Ek Lake (VOYA)—Lead-210 inventories decrease rapidly in Ek Lake to supported levels at 25 cm core depth (Fig. 6). The Euroamerican settlement horizon (1870s) is located at approximately 19 cm. Sedimentation rates have gradually increased in Ek Lake from the 1900s to present; modern rates are approximately four-fold higher than presettlement rates (Fig. 7). This increase in sedimentation rates begins with initial logging in the region.

Biogeochemical records in Ek Lake are more variable than in Cruiser Lake. Carbonate is a minor and relatively constant component of the sediments (~5% by weight; Fig. 8), whereas organic and inorganic content have changed over time. Pre-European sediments are approximately 42% and 52% organic and inorganic content, respectively, by weight. However, a shift occurs after 1950 to greater organic content and lesser inorganic content. Biogenic silica content has decreased over time in Ek Lake sediments from approximately 25% to 22% by weight (Fig. 9). When converted to flux rates, sedimentation of biogenic silica has increased from <1 to over 3 mg/cm^{2}yr at the core top. The increased sedimentation rate, organic content and biogenic silica flux may indicate increased 20th century productivity in Ek Lake.

Peary Lake (VOYA)—The inventory of ^{210}Pb declined monotonically in Peary Lake to supported levels at approximately 15 cm core depth (Fig. 10). The Euroamerican settlement horizon is located at approximately 12 cm core depth. Sedimentation rates in Peary Lake have varied between 0.01 and 0.015 g/cm^{2}yr with a slight peak in the 1960s and 1970s and decreasing sedimentation rates in the most recent decades (Fig. 11).

Loss-on-ignition analysis of Peary Lake shows that the sediments are dominated by >70% inorganic content by weight with a decline after 1950 to 60-70% in the uppermost sediments (Fig. 12). Organic content mirrors inorganic content with approximately 20% by weight in the pre-1950 sediments and an increase to 25-30% by weight in the upper sections of the core. Carbonates remain low throughout the core at <5% by weight except for a small increase in the upper two samples. Biogenic silica varies from 11-14% dry weight with decreasing values from 1870 to 1970 and a small increase in content in the top few samples (Fig. 13). Flux of biogenic silica has remained rather constant over the last 200 years at 1-2 mg/cm^{2}yr.

MODERN DIATOM COMMUNITIES—SURFACE SEDIMENTS

Over 500 diatom taxa were recorded in the 15 samples analyzed from 2006 samples. Forty-four diatom taxa were present at >5% abundance in one sample or >1% abundance in two or more VOYA/MISS/INDU samples ensuring inclusion in our analyses (Table 5). An unconstrained detrended correspondence analysis (DCA) on all species data (2005/2006 samples pooled) showed that species gradients are sufficiently long to justify a unimodal ordination method, such as correspondence analysis (CA). A CA of the species data showed that the two MISS sites are extreme outliers in terms of diatom species community (not illustrated) among the 2005 and 2006 surface sediment samples. For this report the two MISS samples have been removed from further analyses; however, they will be returned to the overall surface sediment calibration set as additional samples are added. Because of a strong arch effect in a CA run without the MISS samples, a DCA was run to explore the differences among diatom communities in the 2005 and 2006 diatom samples. The major axis separated park units with VOYA lakes to the left on axis 1, and the PIRO lakes plus some SLBE lakes grouped to the right. Three SLBE lakes, Round, Tucker, and Shell, plus INDU's Long Lake were separated from the other park clusters. SLBE Shell was especially distinct with its diatom flora dominated by *Denticula kuetzingii*.

The diatom assemblages in sediments from INDU's Long Lake are dominated by fragilarioid species including *Staurosira construens* and var. *venter*, *Staurosirella pinnata*, *Staurosira elliptica* GLEI, and *Pseudostaurosira brevistriata*. The smaller fragilarioid taxa are common in shallow lakes in the periphyton community, especially in the epipelon. The major planktonic diatoms in INDU Long are *Aulacoseira ambigua* and *Fragilaria vaucheriae*. The MISS sites are dominated by the diatom *Cyclotella meneghiniana* and its f. *plana*; both are plankton river forms. VOYA lakes are separated due to the abundance of *Tabellaria* forms and diatoms such as *Eunotia zazuminensis* that are biogeographically constrained to these boreal softwater lakes. The cluster of PIRO and SLBE lakes are dominated by north temperate planktonic species such as *Asterionella formosa*, *Aulacoseira ambigua*, *A. subarctica*, *Cyclotella* (*Discostella*) *stelligera*, *C. michiganiana*, *C. comensis*, *Pseudostaurosira brevistriata* and *Fragilaria crotonensis*.

A canonical correspondence analysis was run to explore the diatom species-environment relationship in SLBE, PIRO, VOYA, and INDU lakes (Figs. 14a). Environmental data were variously transformed to most closely approximate the normal distribution (Table 1). Based on vector length and orientation with CCA axes 1 and 2, the strongest gradients in the species environment data are determined by conductivity, alkalinity and pH, which are aligned with CCA axis 1. Total phosphorus, TN, and Secchi depth form a secondary productivity gradient aligned with CCA axis. 2. Forward selection was used to remove highly correlated variables. For the 2005 and 2006 surface sediments, four environmental variables were found to independently and significantly explain the distribution of diatoms in the GLKN lakes: specific conductance, Ca^{2+}, NH_4, and TN (Fig. 14b). Based on species-environment relationships the VOYA lakes are grouped to the right on axis 1, a testament to their softwater chemistry. The SLBE and PIRO lakes are primarily grouped in quadrant 2 with a few lakes (SLROND, SLTUCK, INLONG, and SLSHLL) located along the TN axis in quadrant 3 (Fig. 14b).

LAND USE HISTORIES—VOYA

Land use histories that may be driving modern or have driven historical environmental change in the GLKN parks are being compiled by park resource managers using literature and historical sources. In temperate North America, initial European settlement, logging and land clearance, damming, development of agriculture, agriculture intensification and abandonment, forest regeneration, introduction of exotic species, fisheries collapse, cottage development, wastewater treatment, and urbanization have been major drivers of change in aquatic ecosystems. More recently, climate change is increasingly being identified as a driver of environmental change in aquatic ecosystems.

The land use and climate history of VOYA have been summarized in Edlund et al. (2008) and will be submitted to GLKN as a separate document. The land use history was prepared as part of a project to determine the environmental histories of the Voyageur large lakes (Rainy, Namakan, and Kabetogama) and was primarily compiled by Larry Kallemeyn, Claire Serieyssol, and Mark Edlund.

CORE STRATIGRAPHIES

Cruiser Lake-VOYA—Fifteen samples were analyzed for subfossil diatom communities from Cruiser Lake covering a period from 1783-2004 AD. A total of 297 diatom taxa was encountered in the core. Throughout this period the diatom community in Cruiser Lake has been dominated by a few planktonic diatom species (Fig. 15). *Discostella stelligera* has remained at almost 40% of the assemblage throughout the core. A morphological variant of *Cyclotella ocellata* (*C. ocellata* Type-1) was a subdominant before Euroamerican settlement and has since been supplanted by *Asterionella formosa*. The three most recent samples have *Cyclotella ocellata* of the type present in the core. A PCA of the diatom assemblages recognized two major stratigraphic zones (Fig. 16), 1783-1872 and 1897-2004, with some additional separation of the near surface samples, 2000-2004 and 1990.

Zone 1 (1783-1872) is characterized by high abundance of *Discostella stelligera* and *Cyclotella ocellata* Type-1. The planktonic species *Asterionella formosa* and *Synedra tenera* are subdominants. Zone 1 represents pre-Euroamerican settlement.

Zone 2 (1897-2004) is characterized by continued dominance by *Discostella stelligera*, decreased abundance of *Cyclotella ocellata* Type-1 and *Synedra tenera*, and increased abundance of *Asterionella formosa*. The top two cores samples, 2000-2004, have increased abundance of *Cyclotella ocellata*, which sets them slightly apart from the other Zone 2 samples. The sample dated 1990 has an odd abundance of the attached species *Encyonema minutum*.

Ek Lake-VOYA—Sediments dated from 1778 to 2000 in Ek Lake were analyzed for diatom remains and over 500 taxa were recorded. Ten species were present at >5% relative abundance including both planktonic and benthic species (Fig. 17). Similar to Cruiser Lake, two predominant planktonic species in the core are *Discostella stelligera* and *Asterionella formosa*;

Aulacoseira tenella and *Eunotia zasuminensis* are the other predominant plankters in Ek Lake. Other subdominant species include the planktonic species *Aulacoseira ambigua* and *Tabellaria flocculosa* IIIp, and basal records of *Puncticulata radiosa*. The benthic diatom flora in Ek Lake is diverse but is dominated by the araphid species *Pseudostaurosira brevistriata*, *Staurosirella pinnata*, and *Staurosira construens* v. *venter*. A principal components analysis of diatom communities in the Ek Lake core separated three biostratigraphic zones dated 1778-1844, 1868-1960, and 1972-2000 (Fig. 18).

Zone 1 (1778-1844) represents the community deposited before logging and Euroamerican settlement in the region. It is primarily characterized by the presence of *Puncticulata radiosa* and lower abundances of *Aulacoseira tenella* and *Discostella stelligera*. The benthic species are well-represented in Zone 1.

Zone 2 (1868-1960) is characterized by higher abundance of *Discostella stelligera*, *Aulacoseira tenella* and *Eunotia zasuminensis*, and the loss of *Puncticulata radiosa* from the Ek Lake flora. Other taxa vary little in abundance within this zone.

Zone 3 (1972-2000) has slightly higher abundance of *Asterionella formosa* and a continued increase in abundance of *Discostella stelligera*. In contrast, *Eunotia zasuminensis* decreases in abundance in Zone 3.

Peary Lake-VOYA—Fifteen sediment samples from the Peary Lake core spanned the period from 1786 to 2001. Over 500 diatom taxa were found in the core with only seven diatom species present at >5% relative abundance downcore (Fig. 19). The sediment assemblage was primarily planktonic species including *Aulacoseira tenella*, *Discostella stelligera*, *Asterionella formosa*, and *Eunotia zasuminensis*. *Aulacoseira ambigua* was present in greater abundance downcore, whereas *Tabellaria flocculosa* IIIp had higher abundance upcore. The only benthic taxon that was found at >5% abundance was *Staurosira construens* v. *venter*; it was more abundant upcore. A principal components analysis of the historical diatom communities in Peary Lake identified three biostratigraphic zones dated 1786-1873, 1895-1912, and 1933-2001 (Fig. 20).

Zone 1 (1786-1873), similar to other VOYA lakes, preserves an assemblage characteristic of pre-Euroamerican settlement conditions. In Peary Lake this zone is characterized by high abundance of *Aulacoseira ambigua* and slightly lower abundance of *A. tenella*. The other common plankters are generally found at similar abundances throughout the core, except for *Tabellaria flocculosa* IIIp, which is nearly absent in Zone 1. Zone 1 is also relatively low in abundance of benthic species.

Zone 2 (1895-1912). Only two samples comprise Zone 2 in the Peary Lake core. The samples seem to be transitional between Zones 1 and 2 recording initial increases in *Tabellaria flocculosa* IIIp and *Staurosira construens* v. *venter*. Zone 2 also sees the start of a decline in abundance of *A. ambigua*, and a peak in abundance of *A. tenella*.

Zone 3 (1933-2001) sediments have a continued decrease in abundance of *Aulacoseira ambigua* offset by increased abundance of *Tabellaria flocculosa* IIIp and *Staurosira construens* v. *venter*. The other planktonic species have relatively consistent abundances in Zone 3.

ENVIRONMENTAL CHANGE IN VOYA AND OTHER GLKN LAKES

The analysis of three sediment cores from VOYA lakes provides a first opportunity to study ecological and biogeochemical changes that have occurred in the last 200 years in some of Voyageurs' smaller lake systems. A companion study on the environmental history of Voyageurs' large lakes (Rainy, Namakan, Kabetogama), and an upgradient and undammed lake (Lac La Croix), reported that diatom communities in all the large lakes were initially impacted by first-cut logging and Euroamerican settlement (Edlund et al. 2008). Damming occurred nearly simultaneously with large scale logging in Voyageurs, and in the Namakan-Kabetogama Reservoir, the cores further record increases in sedimentation rates following damming. More interesting in the large lake cores are diatom community shifts after the 1970s. While these may be the result of climate change, other factors including land use (e.g., continued pulpwood cutting in the watershed, increases in beaver numbers) and hydromanagement also explain significant portions of the variance in the diatom communities (Edlund et al. 2008, Serieyssol et al. in press).

Similar to the large lakes, Voyageurs' inland lakes show changes in their diatom communities and biogeochemistry in the last 200 years. However, in contrast to other GLKN lakes we have investigated (e.g., Manitou Lake, SLBE), diatom communities and geochemical records in VOYA do not show such dramatic changes. Two types of responses are common among the three lakes. First, sedimentation rates increase in all three lakes. In Cruiser and Peary Lakes, sedimentation rates increase after the 1920s, whereas in Ek Lake the increase began earlier, around 1900. Logging records from the Voyageurs region (Edlund et al. 2008) generally peak in the early 20th century and it is conceivable that the increases in sedimentation rates are a result of logging. Second, all three lakes show their greatest shifts in diatom communities in the late 1800s, ranging from a shift in Cruiser Lake between 1872 and 1897, in Ek Lake between 1844 and 1868, and in Peary Lake between 1873 and 1895. For northern Minnesota, this time frame closely corresponds to initial Euroamerican interests and settlement in the region (Edlund et al. 2008). The response of the diatom community may have been a harbinger of bigger changes brought on by larger-scale logging. Historical records indicate that initial cutting in the region in the 1800s took place adjacent to lakes, which could have provided the trigger for slightly earlier changes in the diatom communities in comparison to the sedimentation rates.

After settlement and first cut logging in VOYA, the lakes had varying environmental histories. Cruiser Lake had no clear biostratigraphic zonation after Euroamerican settlement except for the top two samples which were slightly separated from the previous decades. Although there are no substantial changes in weight percent organics, inorganics, or carbonates, biogenic silica content decreases and flux of all geochemical components increases upcore, suggesting some subtle ecological changes have occurred in the 20th century. The greater abundance of *Asterionella formosa* in post-settlement core levels suggests potential minor increases in nutrient loading.

Ek Lake had two main biostratigraphic zones in post-settlement sediments with a community shift identified between the 1960 and 1972 samples. The zone from 1972 to 2000 is characterized by increased abundance of *Asterionella formosa* and decrease abundance of *Eunotia zasuminensis*. Very little is known of the ecology of *Eunotia zasuminensis* apart from its planktonic autecology (most *Eunotia* are attached species) and distribution in softwater and slightly acidic lakes. *Asterionella formosa*, on the other hand, commonly responds to increased nutrient loading and in some lake systems is an indicator of eutrophication. We would not suggest that Ek Lake is a eutrophic system, but nutrient dynamics may have changed in the course of its history. Based on modern water quality measurements, Ek Lake would be considered mesotrophic (TSI; Elias and VanderMeulen 2008). As for the timing of these changes in VOYA, the 1960s represent a period of rapid increase in beaver populations on the peninsula which may have driven hydrological changes in Ek Lake.

After Euroamerican settlement, Peary Lake's diatom communities went through a brief transitional period that corresponded to the peak of logging in the region (samples dated 1895-1912). Similar to Cruiser and Ek Lakes, *Asterionella formosa* increased in abundance following settlement, and similar to Ek Lake, *Tabellaria flocculosa* IIIp increased in abundance in Peary Lake. Sedimentation rates also increased in Peary Lake after first cut logging from 1920 to 1970, before decreasing up core. The most recent biostratigraphic zone (1933-2001) in Peary Lake shows little variability in the diatom community.

In contrast to the larger VOYA lakes and some of the more easterly GLKN lakes, there is not a clear signal of ecological change in the inland VOYA lakes that might be associated with recent climate change. In the large VOYA lakes and in nearby Lac La Croix, shifts in diatom communities occur in the late 1970s or early 1980s in a time frame strongly correlated to recent warming trends (Edlund et al. 2008, Serieyssol et al. in press). Similar shifts in diatom communities have occurred in a large number of arctic, boreal and sub boreal lakes (Smol et al. 2005, Rühland et al. 2008). The ecological changes in the large VOYA lakes are also correlated to landuse trends in the region, especially continued pulpwood cutting and beaver numbers. We anticipated that the smaller lakes might have stronger responses to climate drivers, but it is not apparent in these data. Also of importance is to note that the inland lakes were not expected to be responding to some of the broader landuse drivers of change (logging) that are occurring in the watersheds of the larger VOYA lakes and continue to impact them.

A final statistical technique was applied to all GLKN cores counted to date to explore potential environmental drivers of community change. Diatom communities in the six cores (Grand Sable, Shell, Manitou, Cruiser, Ek, Peary) were passively plotted on the CCA (Fig. 14b) of species-environment relationships for the 2005 and 2006 surface sediments. When possible, samples were connected in a chronosequence. Two patterns were apparent in the diatom communities of the cored lakes in relation to the broader environmental-relationships of all GLKN lakes. First, four of the lakes show very little change in the last 200 years. These lakes include VOYA's Cruiser, Ek, and Peary Lakes, and PIRO's Grand Sable Lake (Figs. 21-24). Diatom communities in all four lakes are tightly clustered in the passive plots indicating that although we can resolve biostratigraphic changes in the cores, these changes are not large in the context of lake types and diatom communities in the GLKN parks. It should be further noted

that these four lakes are in areas that have had lesser amounts of land use change with primarily initial logging and insignificant amounts of agricultural and urbanization in their histories. In contrast, SLBE's Shell Lake and Manitou Lake show more dramatic changes in their diatom communities in the last 200 years. Shell Lake has two samples from 1941-1953 that are separated from all other Shell Lake core samples (Fig. 25). These two samples are stratigraphically separated by peaks in abundance of several benthic diatom species (see first annual report) and the trajectory suggests that there may have been several decades of slightly lower nutrients in Shell Lake, perhaps associated with the collapse of farms in the SLBE region during the 1940s and 1950s.

The lake that shows the largest directional change in its diatom community is Manitou Lake (Fig. 26; SLBE). From pre-settlement to 1972, the diatom community shifts along axis two in line with the total nitrogen axis. Total N is highly correlated to other nutrients and productivity measures (Fig. 14a) and suggests that nutrient levels have declined in Manitou Lake. Samples dated from 1982-2002 in Manitou Lake move along a slightly different trajectory, continuing down the nutrient gradient, but also moving left on axis 1 along the increasing direction of the correlated conductivity, pH, Ca^{2+}, ammonium, and alkalinity vectors. The large changes in recent diatom communities suggests that nutrient dynamics and pH-Alk-conductivity relationships may be changing in Manitou Lake, and the timing of these changes does not correspond to any major landuse on Manitou Island but rather are more closely correlated to climate records. It will be very interesting to see if similar shifts occur in the cores collected in 2008 from Florence Lake and Bass Lake at SLBE.

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TABLES

Table 1. Transformations used on environmental variables for multivariate analyses. Among the suite of possible transformations, these resulted in near normal distributions for each variable.

Variable	Transformation	Units
Chla	log10	µg/L
TP	log10	µg/L
TN	log10	mg/L
NO3NO2	log10	mg/L
NH4	log10	mg/L
DOC	log10	mg/L
Alk	log10	mg/L
Cl	1/Cl	mg/L
SO4	1/SO4	mg/L
Ca	log10	mg/L
Na	1/Na	mg/L
K	1/K	mg/L
Mg	log10	mg/L
SiO2	log10	mg/L
Secchi	log10	m
pH	no transformation	std units
EC25	log10	µS/cm

Table 2a. Mean ice-free 2005-2006 water quality variables from PIRO, SLBE, VOYA, MISS, and INDU lakes. Blue values are SCWRS lab data (see Elias 2007 for interlab variability). Twelve of 22 VOYA lakes sampled in 2006 are listed because diatom analysis has been completed on only those 12 lakes. The remainder will be analyzed in 2008.

PARK/lake	Chl-a	TP	TKN	TN	NO_3/NO_2-N	NH4-N	DOC	Alkalinity	Cl
	µg/L	µg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
PIRO									
Grand Sable	3.33	8.11	0.36	0.21	0.008	0.06	5.6	46	0.3
Trappers	3.29	10	0.75	0.74	0.01	0.11	9.7	70	0.28
Chapel	2.9	8.58	0.36	0.23	0.016	0.09	7.3	86	0.28
Beaver	5.1	12.22	0.2	0.18	0.006	0.07	3.6	76	0.37
Little Beaver	9.4	21.2	0.42	0.31	0.005	0.07	5.5	66	0.29
Miners	1.99	16.34	0.43	0.42	0.097	0.13	5.6	142	1.24
SLBE									
Manitou	3.88	8.66	0.435	0.41	0.006	0.13	6.7	134	0.52
Florence	6.86	14.1	0.68	0.65	0.011	0.03	8.9	43.75	0.75
Shell	2.15	12.61	0.785	0.96	0.011	0.07	10	108.5	1.16
Bass (L)	3.24	9.26	0.82	0.59	0.008	0.13	9.4	100.25	4.51
School	4.5	21.9	0.815	1.08	0.006	0.04	13.4	89.25	9.45
Tucker	3.12	17.5	0.8	0.76	0.007	0.025	12	123	1.26
North Bar	4.33	10.9	0.4	0.51	0.122	0.06	3.5	145.5	4.07
Loon	3.39	10.68	0.37	0.22	0.012	0.02	3.3	132.25	7.87
Round	3.88	10.87	0.695	0.56	0.007	0.05	7.2	129.5	18.25
VOYA									
Agnes	8.00	23.33	N/A	0.64	0.02	0.02	16.33	7.33	0.87
Brown	3.33	7.00	N/A	0.43	0.00	0.01	10.67	5.33	0.63
Cruiser	1.67	3.67	N/A	0.20	0.00	0.00	4.23	7.33	0.37
Ek	8.00	16.33	N/A	0.64	0.01	0.02	13.00	9.33	0.63
Little Shoepack	3.50	7.33	N/A	0.42	0.04	0.01	12.00	5.50	0.73
Little Trout	7.00	12.67	N/A	0.53	0.00	0.01	11.67	8.00	0.63
Locator	1.00	5.00	N/A	0.27	0.01	0.00	5.07	13.00	0.47
Mukooda	3.33	8.33	N/A	0.37	0.05	0.01	6.07	20.00	0.50
Peary	8.33	18.00	N/A	0.53	0.01	0.01	10.47	7.67	0.57
Quarterline	2.00	5.67	N/A	0.41	0.02	0.01	9.90	6.33	0.60
Ryan	3.67	9.00	N/A	0.49	0.01	0.01	12.00	6.00	0.57
Shoepack	7.67	28.67	N/A	0.66	0.01	0.03	15.33	7.00	0.87
MISS									
Coon Rpds	27.55	63.50	N/A	1.40	0.60	0.01	7.70	152.57	17.07
Spring Lk	24.65	138.13	N/A	4.06	3.22	0.10	7.67	180.57	37.27
INDU									
Long	3.33	22.60	N/A	0.54	0.01	0.02	8.68	96.20	24.52

Table 2b. Mean ice-free 2005-2006 water quality variables from PIRO, SLBE, VOYA, MISS, and INDU lakes. Blue values are SCWRS lab data (see Elias 2007 for interlab variability). See additional explanation in Table 2a.

PARK/lake	SO4	Ca	Na	K	Mg	SiO$_2$	Secchi depth	pH	EC25
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	m	std. units	µS/cm
PIRO									
Grand Sable	4.47	14.09	0.93	0.75	5.09	4.75	3.9	8	110
Trappers	4.45	23.26	1.06	0.59	5.52	5.88	NA	8.5	148
Chapel	8.31	21.91	0.8	0.68	10.49	4.41	3.6	8.1	187
Beaver	6.65	26	1.09	0.62	5.46	9.29	3.9	8.2	164
Little Beaver	7.52	20.69	1.03	0.63	5.74	6.52	2.8	8.2	165
Miners	8.41	32.77	1.3	0.63	16.83	6.6	2.5	7.8	278
SLBE									
Manitou	6.39	33.51	1.38	0.55	15.52	1.17	2.6	8.6	270
Florence	3.15	12.97	0.63	0.63	5.74	0.39	2.5	8.4	111
Shell	20.02	32.94	1.57	0.41	14.32	13.66	3	8.5	262
Bass (L)	3.14	31.49	2.98	0.92	10.08	3.65	3.2	8.6	229
School	5.81	24.56	3.51	0.7	10.78	16.36	NA	8.8	212
Tucker	4.83	35.08	1.05	0.32	12.67	7.72	NA	8.3	262
North Bar	9.41	44.29	1.59	0.57	15.38	5.48	2.2	8.3	329
Loon	10.05	41.99	5.78	0.66	12.42	7.14	3.2	8.4	310
Round	9.67	29.62	12.04	0.59	15.91	6.72	4.6	8.7	319
VOYA									
Agnes	1.49	1.91	1.13	0.56	1.00	1.18	1.10	6.28	22.00
Brown	2.04	2.09	1.20	0.61	0.96	2.10	2.49	7.34	21.00
Cruiser	2.56	2.01	0.80	0.53	0.77	0.85	7.60	7.14	19.67
Ek	2.19	2.99	1.39	0.78	1.35	0.58	1.95	7.03	32.50
Little Shoepack	3.08	2.44	1.16	0.68	1.10	1.60	2.70	6.83	24.67
Little Trout	2.63	1.97	1.20	0.58	1.02	1.07	2.35	7.01	22.33
Locator	3.03	4.05	1.00	0.56	2.05	0.30	6.29	7.71	35.33
Mukooda	2.04	5.70	1.35	0.80	2.94	0.30	5.32	7.95	52.67
Peary	2.10	2.51	1.27	0.63	1.22	0.80	2.30	7.53	30.67
Quarterline	3.00	2.37	1.03	0.68	1.06	2.10	3.86	7.09	24.00
Ryan	3.59	2.61	1.21	0.50	1.04	2.60	2.79	6.90	28.67
Shoepack	3.48	2.23	1.21	0.61	1.02	1.10	1.38	6.38	22.67
MISS									
Coon Rpds	19.13	44.62	9.92	2.58	17.87	8.70	0.64	8.52	391.44
Spring Lk	79.78	63.24	25.49	3.98	30.71	12.13	0.32	8.29	649.84
INDU									
Long	9.08	29.59	11.20	1.33	9.46	1.72	1.00	7.03	297.67

Table 3. Surface sediment samples collected from VOYA, INDU, MISS in 2006 for diatom analysis. Samples without codes were rejected for analysis (UMinn852, INDU George) or will be analyzed in 2008 (VOYA samples and a new collection of UMinn852). VOYA lakes and coordinates listed in blue font represent averaged coordinates from each lake's 2006 WQ quality sampling readings.

Lake	Code	Date	Zone	Lat N	Long W	UTM northing	UTM easting	Park	Core depth (cm)
Agnes	VOAGNS	20060921	15	48.46789	92.81259	5368323	0513853	VOYA	0-1
Beast		20060923	15	48.50823	92.75954	5372818	0517760	VOYA	0-1
Brown	VOBRWN	20060927	15	48.51635	92.79641	5373713	0515035	VOYA	0-1
Cruiser	VOCRUS	20060926	15	48.49899	92.81183	5371780	0513901	VOYA	0-1
Ek	VOEK	20060921	15	48.46993	92.835	5368546	0512196	VOYA	0-1
Fishmouth		20060927	15	48.52741	92.78154	5374945	516129	VOYA	0-1
Jorgens		20060918	15	48.48404	92.84797	5370113	0511234	VOYA	0-1
Little Shoepack	VOLTSH	200609NA	15	48.49006	92.88129	5370778	0508771	VOYA	0-1
Little Trout	VOLTTR	20060920	15	48.39794	92.52526	5360640	0535140	VOYA	0-1
Locator	VOLOCA	20060925	15	48°32.394'	93°00.231'	5376311	500284	VOYA	0-1
Loiten		20060925	15	48.52753	92.92865	5374938	0505268	VOYA	0-1
Mukooda	VOMUKO	20060920	15	48.33404	92.48669	5353556	0538043	VOYA	0-1
Net		20060924	15	48.39551	92.65661	5360318	0525419	VOYA	0-1
O'Leary		20060920	15	48.41597	92.5325	5362641	0534592	VOYA	0-1
Oslo		20060927	15	48.51684	92.80659	5373766	0514283	VOYA	0-1
Peary	VOPEAR	20060927	15	48.52472	92.7726	5374648	0516790	VOYA	0-1
Quarterline		20060918	15	48.47683	92.84521	5369312	0511440	VOYA	0-1
Quill	VOQUIL	20060925	15	48.53244	92.95327	5375483	0503450	VOYA	0-1
Ryan	VORYAN	20060927	15	48.5192	92.70761	5374051	0521591	VOYA	0-1
Shoepack	VOSHOE	200609NA	15	48.49837	92.88759	5371701	0508304	VOYA	0-1
Tooth		20060924	15	48.39856	92.64328	5360662	0526404	VOYA	0-1
War Club		20060925	15	48°32.240'	92°58.976'	5376057	0501193	VOYA	0-1
Coon Rpds	MSCNRP	20061011	15	45°09.075'	93°19.670'	4999805	525770	MISS	0-1
UMinn852		20061011	15	44°58.212'	93°14.258'	4979668	518739	MISS	0-1
Spring Lk	MSSPLK	20061012	15	44°46.018'	92°57.544'	4957065	496761	MISS	0-1
George		20061003	16	41.52594	87.27808	4597181	0476800	INDU	0-1
Long	INLONG	20061003	16	41.61528	87.21251	4607084	0482295	INDU	0-1

Table 4. Lakes cored in 2006, length of core recovered, and sectioning strategy.

Lake	Coring Location Date	Park	Z (m)	Core length (cm)	Field and lab sectioned (cm)
Ek Lake	48°28'11.1"N 92°50'9.6"W 20060807	VOYA	5.64	1.35	1-cm inc to 60 cm
Peary Lake	48°31'27.22"N 92°46'17.9" 20060808	VOYA	5.03	0.88	1-cm inc to 85 cm
Cruiser Lake	48°29'51.1"N 92°48'8.1"W 20060809	VOYA	21.72	0.88	1-cm inc to 60 cm

Table 5a. Diatom taxa present at >5% relative abundance in one sample or >1% abundance in two or more samples from surface sediments collected in 2006 from VOYA, INDU, MISS lakes.

Code	Taxon	Max Abund	Agnes	Brown	Coon Rapids	Cruiser	Ek
			VOAGNS	VOBRWN	MSCNRP	VOCRUS	VOEK
TABFLO3P	*Tabellaria flocculosa Strain IIIp*	0.4182	0.0259	0.0274		0.0243	
CYCOCELL	*Cyclotella ocellata*	0.3560			0.0024	0.1278	
ASTFORMO	*Asterionella formosa*	0.3535	0.2773	0.0928		0.2718	0.1782
CYCSTELL	*Discostella stelligera*	0.3266		0.1688	0.0048	0.3266	0.0856
CYCMENEG	*Cyclotella meneghiniana*	0.2524		0.0021	0.2524		
SRACONST	*Staurosira construens*	0.2257			0.0048		0.0208
AULAMBIG	*Aulacoseira ambigua*	0.2237	0.0333	0.1814	0.0143		0.0556
EUNZASUM	*Eunotia zazuminensis*	0.2163	0.2163	0.0084			
SLLPINNA	*Staurosirella pinnata*	0.1512	0.0092	0.0042		0.0020	0.0162
COCPLALI	*Cocconeis placentula var. lineata*	0.1357			0.1357		
FRAEXIGU	*Fragilariforma exilis*	0.1324		0.0021			
SRACONVE	*Staurosira construens var. venter*	0.1227	0.0370	0.0654	0.0214	0.0081	0.1227
TABFLOCC	*Tabellaria flocculosa*	0.1088					0.1088
AULITALI	*Aulacoseira italica*	0.1050				0.0122	0.0208
AULTENEL	*Aulacoseira tenella*	0.1561	0.0943	0.1561			
PRABREVI	*Pseudostaurosira brevistriata*	0.0948	0.0092	0.0084	0.0095		0.0347
SRAELLIP	*Staurosira elliptica GLEI*	0.0903					
SUSMINUS	*Stephanodiscus minutulus*	0.0840			0.0167		
CYCMENPL	*Cyclotella meneghiniana fo. plana*	0.0807			0.0167		
NAVCAPRA	*Navicula capitatoradiata*	0.0714			0.0714		
SUSPARVU	*Stephanodiscus parvus*	0.0672			0.0048		
CSPTHOLI	*Cyclostephanos tholiformis*	0.0559			0.0048		
ACHMINUT	*Achnanthidium minutissimum*	0.0547	0.0129	0.0253	0.0048	0.0081	0.0208
CSPINVIS	*Cyclostephanos invisitatus*	0.0538			0.0286		
CYCBODLE	*Puncticulata lemanica*	0.0373		0.0274		0.0081	0.0347
AULGRANU	*Aulacoseira granulata*	0.0373			0.0310		
CYCMICHI	*Cyclotella michiganiana*	0.0352				0.0081	
FRANANAN	*Synedra nana*	0.0345				0.0345	
TABFLOLI	*Tabellaria flocculosa var. linearis*	0.0336	0.0092	0.0021			
AULSUBAR	*Aulacoseira subarctica*	0.0314	0.0314				
CYCATOMU	*Cyclotella atomus*	0.0290			0.0214		
CYCBODAN	*Puncticulata bodanica*	0.0286				0.0041	
EUNPECTI	*Eunotia pectinalis*	0.0277	0.0277				
NITPALEA	*Nitzschia palea*	0.0228	0.0018	0.0021	0.0095	0.0081	0.0046
SUSHANTZ	*Stephanodiscus hantzschii f. hantzschii*	0.0228			0.0024		
FRAVAUCH	*Fragilaria vaucheriae*	0.0226					0.0162
BRANEOEX	*Brachysira neoexilis*	0.0215		0.0021			0.0023
NAVLEPTO	*Navicula leptostriata*	0.0205		0.0021			
TABFLOC3	*Tabellaria flocculosa Strain III*	0.0201	0.0037	0.0042			
CYCSERAT	*Cyclotella seratula*	0.0183	0.0055		0.0071	0.0020	0.0093
TABFLOC4	*Tabellaria flocculosa Strain IV*	0.0176					

SYNDELIC	*Synedra delicatissima*	0.0145	0.0037			0.0071	0.0020	
SYNNA1	*Synedra sp.*	0.0134	0.0018					
NAVRADIO	*Navicula radiosa*	0.0127		0.0127			0.0061	0.0046

Table 5b. Diatom taxa present at >5% relative abundance in one sample or >1% abundance in two or more samples from surface sediments collected in 2006 from VOYA, INDU, MISS lakes.

Code	Little Shoepack VOLTSH	Little Trout VOLTTR	Locator VOLOCA	Long INDU INLONG	Mukooda VOMUKO	Peary VOPEAR	Quill VOQUIL	Ryan VORYAN	Shoepack VOSHOE	Spring Lk RM882 MSSPLK
TABFLO3P	0.1085	0.0198	0.4182		0.0546	0.0994	0.0820	0.0068	0.0447	
CYCOCELL		0.3560			0.0126					
ASTFORMO	0.0390	0.0879	0.0973		0.1765	0.1400	0.3535	0.0342	0.1477	0.0021
CYCSTELL	0.1475	0.2747	0.1573		0.0819	0.0872	0.0566	0.0046	0.0358	0.0124
CYCMENEG										0.2195
SRACONST				0.2257						
AULAMBIG	0.1323			0.0564		0.0974	0.0078	0.0616	0.2237	0.0269
EUNZASUM	0.1649		0.0207			0.0933			0.1767	
SLLPINNA		0.0022		0.1512	0.0189	0.0243	0.0039	0.0639		
COCPLALI				0.0113		0.0081				0.0041
FRAEXIGU								0.1324		
SRACONVE	0.0803	0.0022	0.0021	0.0700	0.0084	0.0162	0.0156	0.1210	0.0022	0.0041
TABFLOCC										
AULITALI				0.0203	0.1050	0.0020	0.0039	0.0114	0.0559	0.0041
AULTENEL	0.0868		0.1159			0.1034	0.0254	0.0388	0.1029	
PRABREVI				0.0948				0.0479	0.0134	0.0062
SRAELLIP				0.0903						
SUSMINUS		0.0044			0.0840					0.0580
CYCMENPL										0.0807
NAVCAPRA										0.0041
SUSPARVU					0.0672					0.0559
CSPTHOLI										0.0559
ACHMINUT	0.0369	0.0286	0.0124	0.0135	0.0168	0.0203	0.0547	0.0251	0.0089	
CSPINVIS										0.0538
CYCBODLE			0.0373		0.0168	0.0101		0.0023	0.0022	
AULGRANU				0.0090						0.0373
CYCMICHI		0.0352			0.0252					
FRANANAN	0.0043	0.0242			0.0021	0.0020				0.0062
TABFLOLI	0.0022		0.0248	0.0090	0.0336	0.0142	0.0117	0.0023		
AULSUBAR	0.0043	0.0308								0.0083
CYCATOMU										0.0290
CYCBODAN	0.0130	0.0286			0.0105	0.0101	0.0176			
EUNPECTI	0.0022						0.0215		0.0045	
NITPALEA	0.0022	0.0044	0.0041	0.0023	0.0042	0.0020	0.0020	0.0046	0.0022	0.0228
SUSHANTZ					0.0147					0.0228
FRAVAUCH				0.0226						
BRANEOEX	0.0043				0.0063		0.0215	0.0137		
NAVLEPTO						0.0020	0.0059	0.0205	0.0112	
TABFLOC3	0.0108	0.0110	0.0021			0.0081	0.0020		0.0201	
CYCSERAT								0.0183		0.0124
TABFLOC4			0.0041			0.0122	0.0176			
SYNDELIC		0.0110	0.0021	0.0023	0.0042					0.0145

SYNNA1		0.0110	0.0041						0.0134	
NAVRADIO		0.0044	0.0041	0.0045	0.0105					

FIGURES
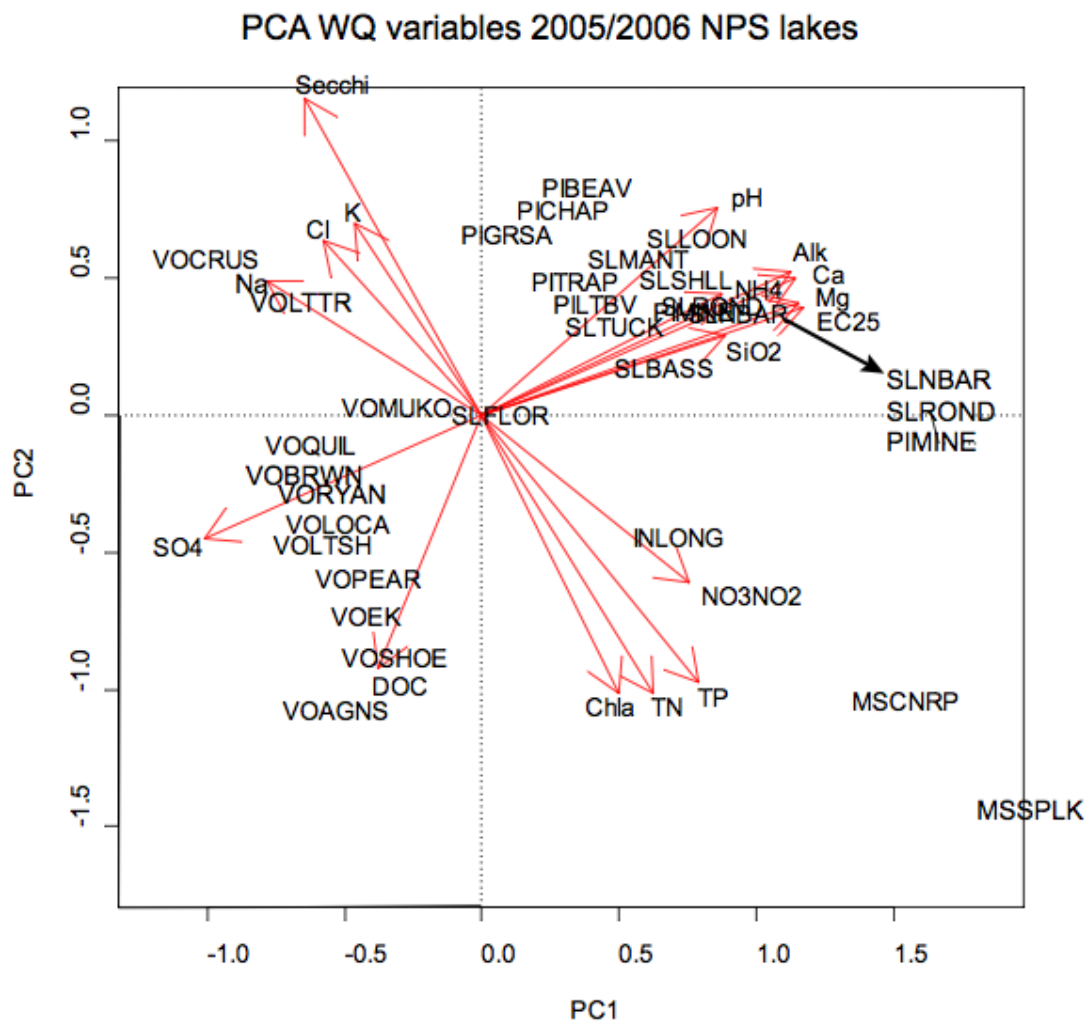
Figure 1a. Principal components analysis (PCA) of twelve water quality variables from 2005 and 2006 sampling of SLBE, PIRO, VOYA, INDU, MISS lakes. Environmental vectors scaled at 0.7.
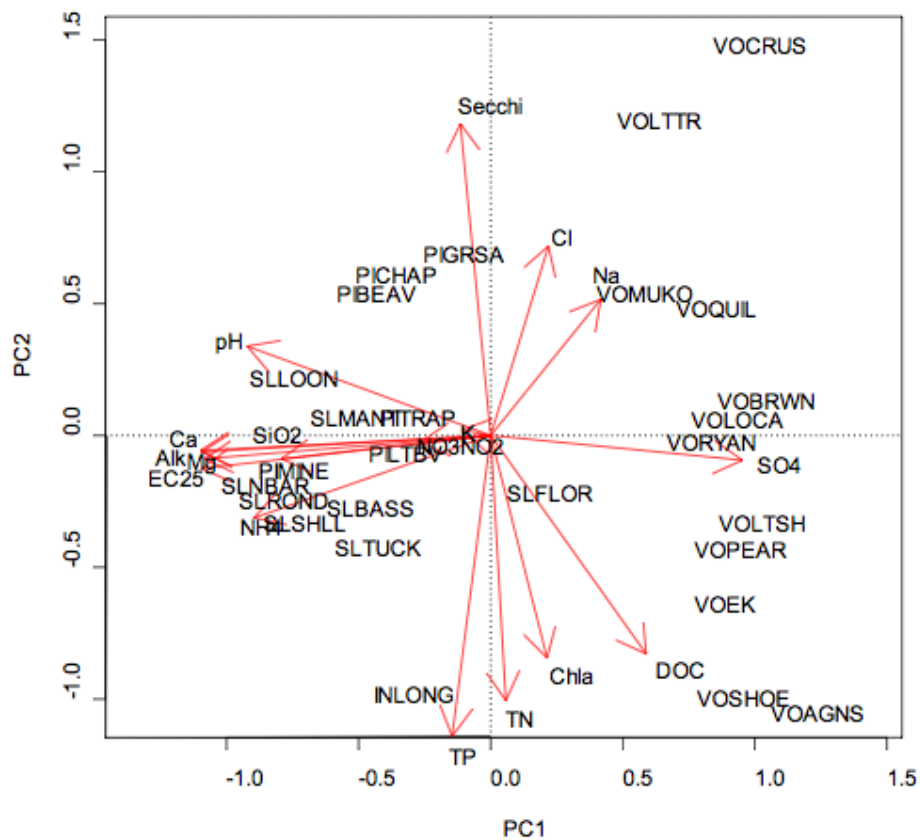
Figure 1b. Principal components analysis (PCA) of twelve water quality variables from 2005 and 2006 sampling of SLBE, PIRO, VOYA, and INDU lakes. MISS lakes removed from analysis. Environmental vectors scaled at 0.7.
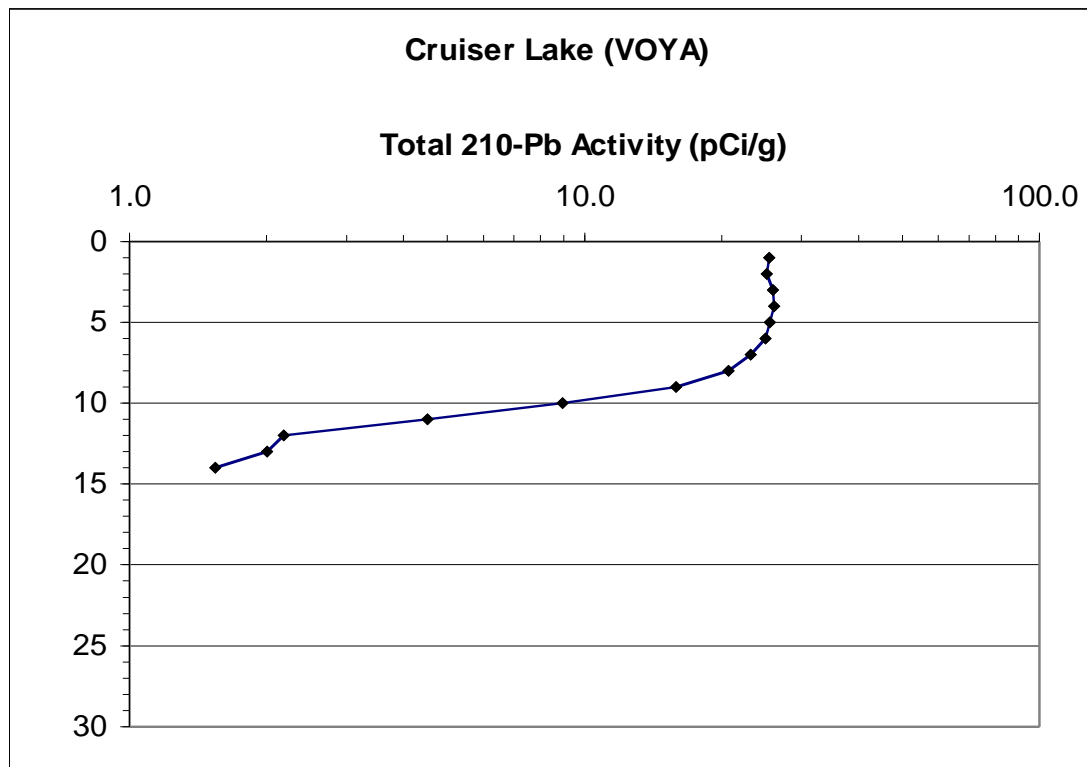
Figure 2. Total ^{210}Pb activity against core depth (cm), Cruiser Lake (VOYA).
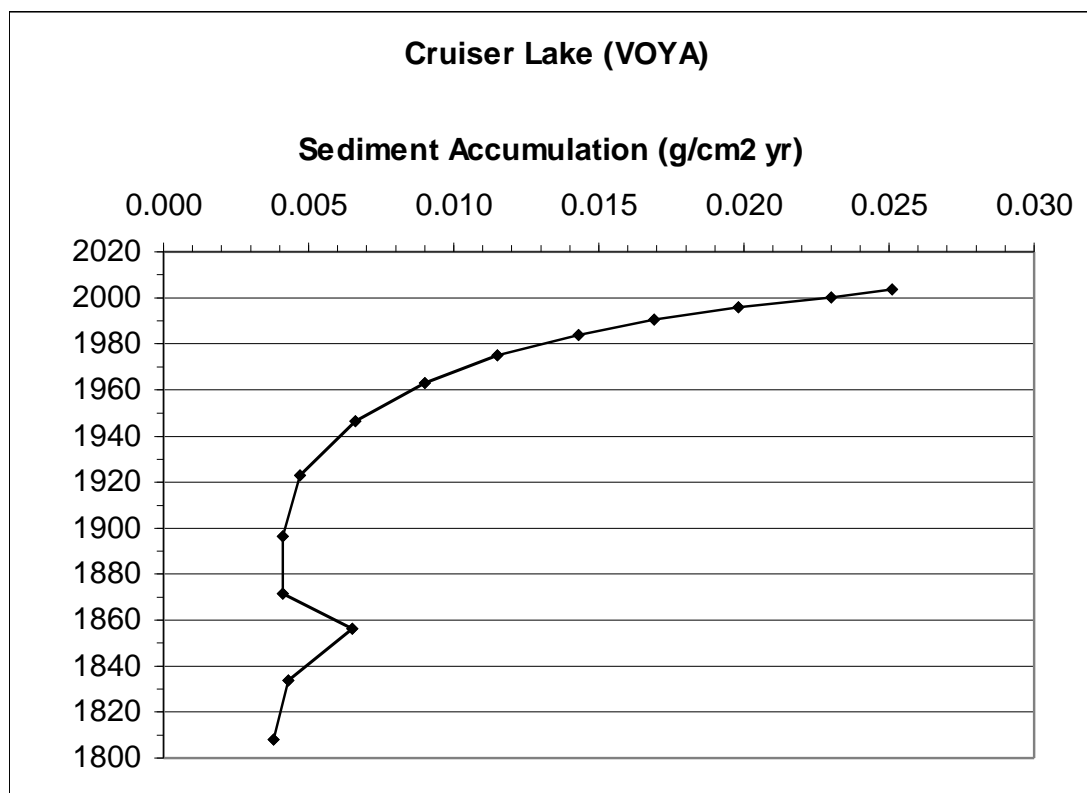
Figure 3. Sediment accumulation rate, Cruiser Lake (VOYA), g cm^{-2} yr^{-1}.
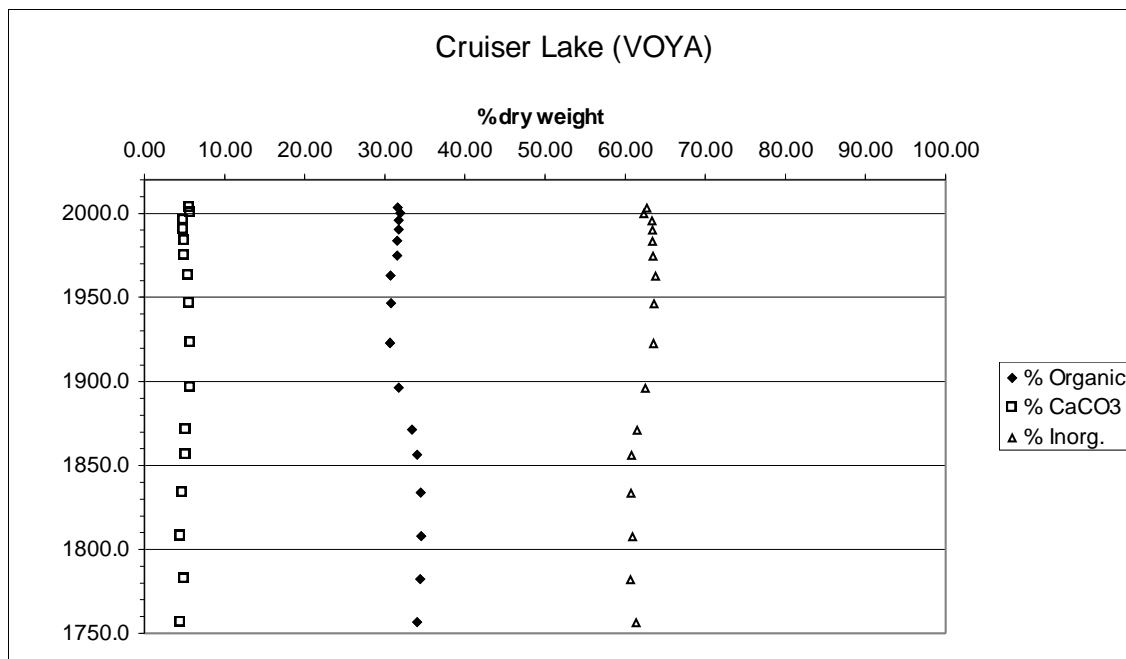
Figure 4. Percent concentration of CaCO₃, organic carbon and inorganic matter in Cruiser Lake (VOYA) core.
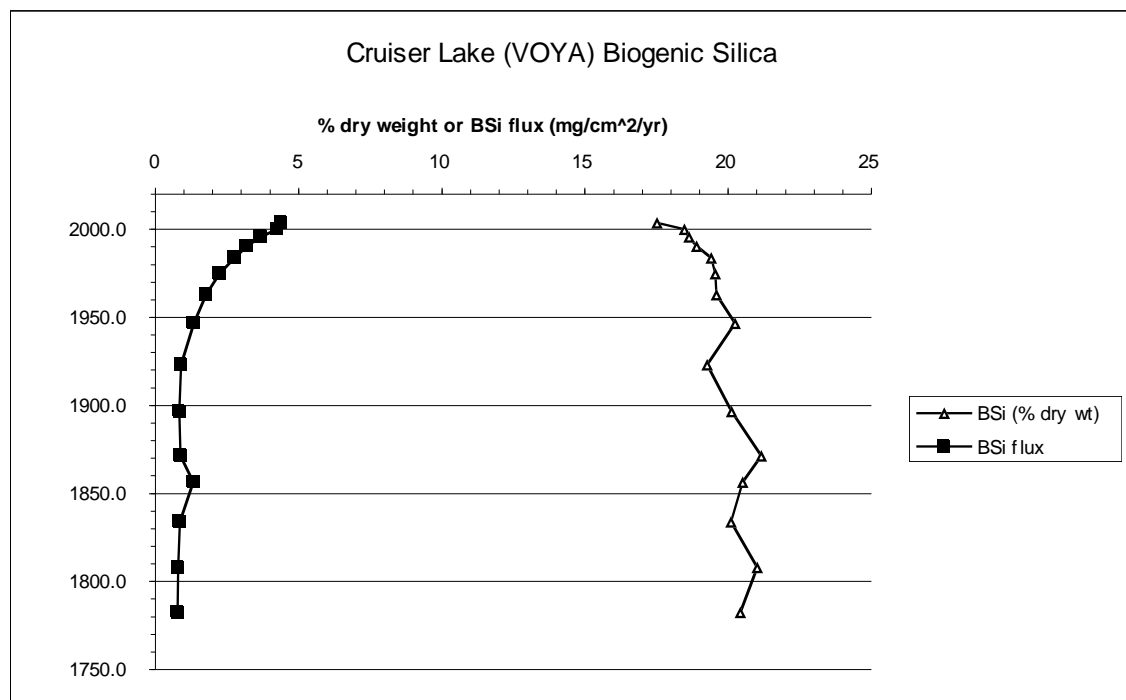
Figure 5. Biogenic silica dry weight percent and flux (mg cm^{-2} yr^{-1}), Cruiser Lake (VOYA).

30

Ek Lake (VOYA)

Total 210-Pb Activity (pCi/g)
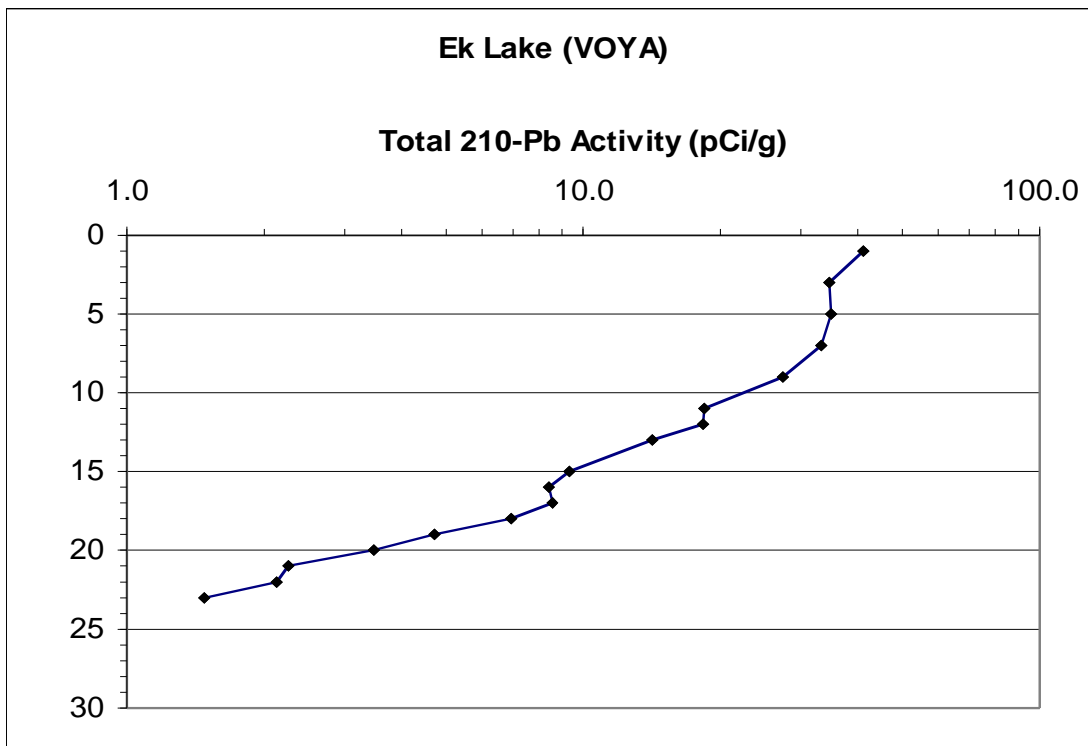
Figure 6. Total ^{210}Pb activity against core depth (cm), Ek Lake (VOYA).

Ek Lake (VOYA)

Sediment Accumulation (g/cm2 yr)
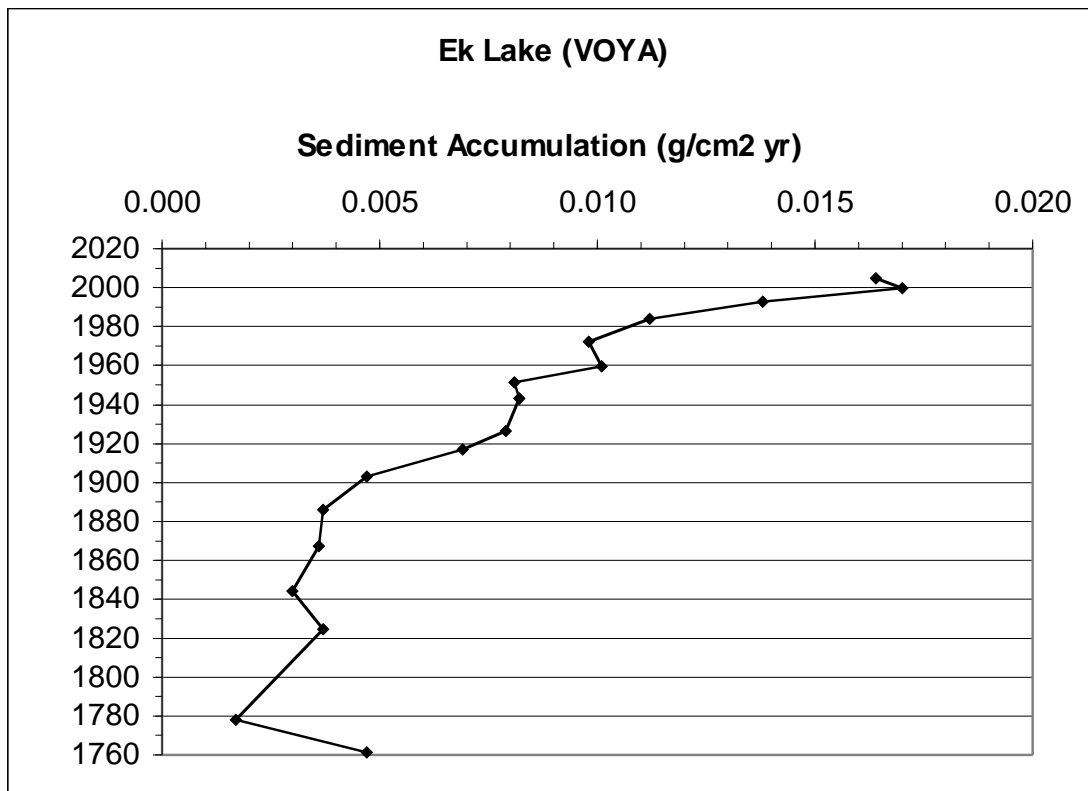
Figure 7. Sediment accumulation rate, Ek Lake (VOYA), g cm^{-2} yr^{-1}.

31
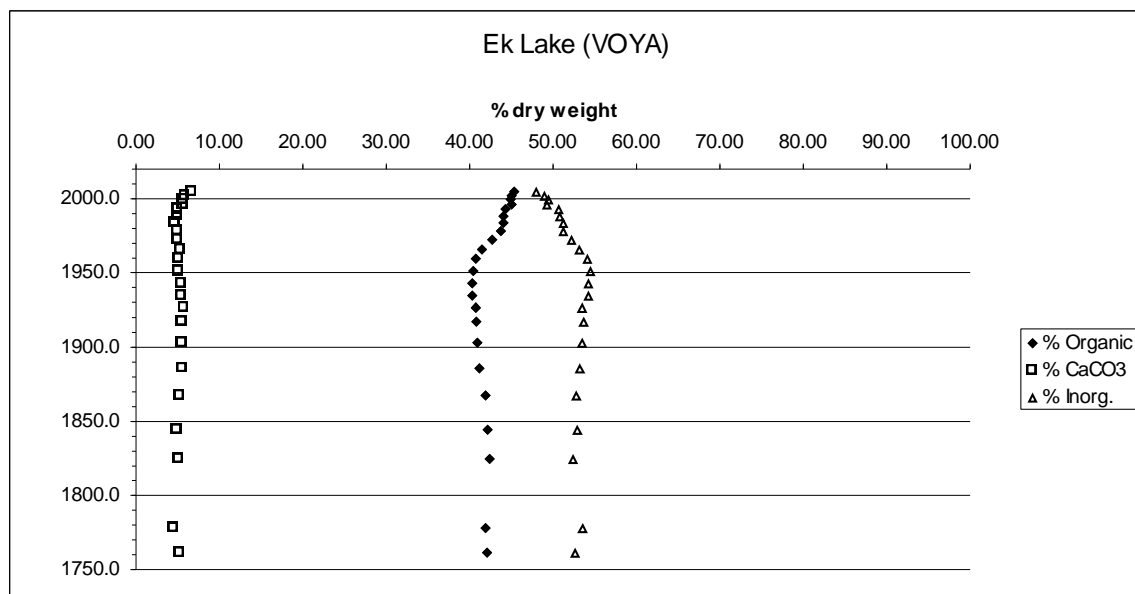
Figure 8. Percent concentration of CaCO₃, organic carbon and inorganic matter in Ek Lake (VOYA) core.
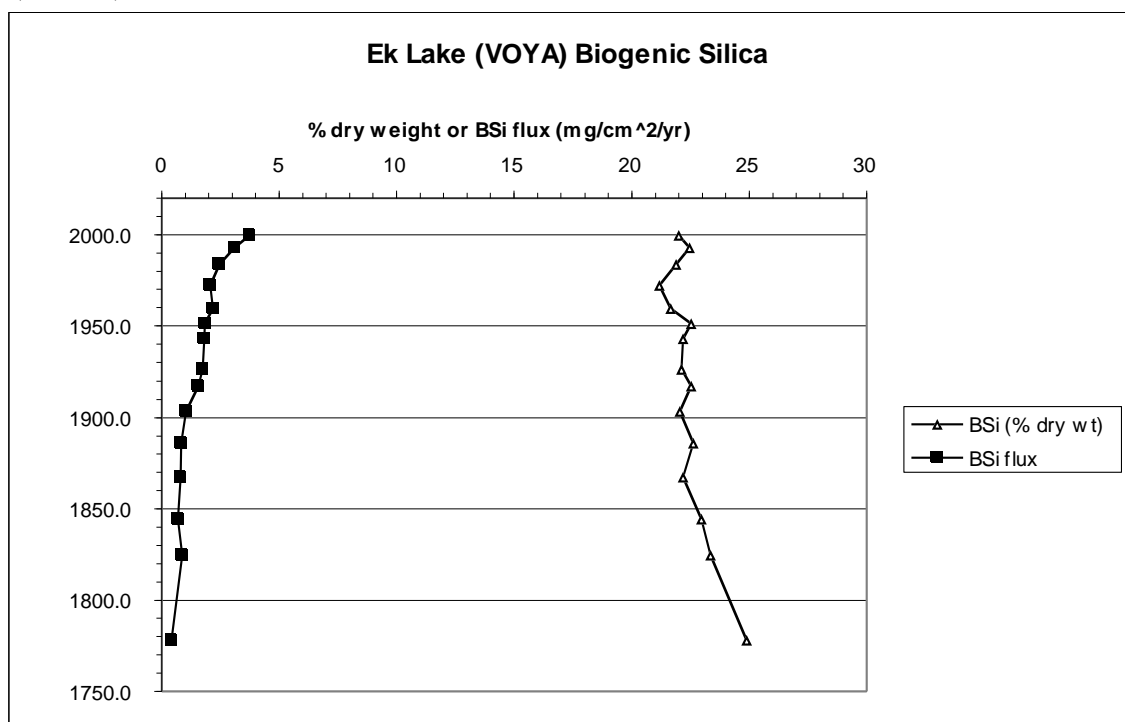
Figure 9. Biogenic silica dry weight percent and flux (mg cm^{-2} yr^{-1}), Ek Lake (VOYA).
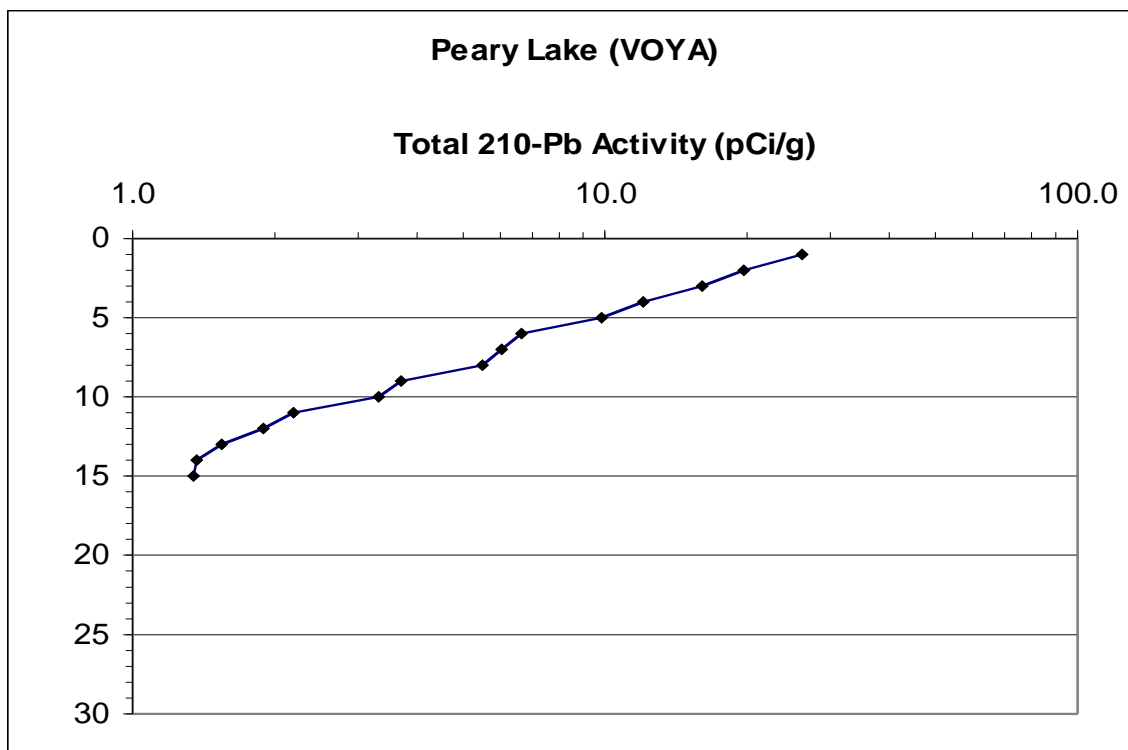
Figure 10. Total ^{210}Pb activity against core depth (cm), Peary Lake (VOYA).
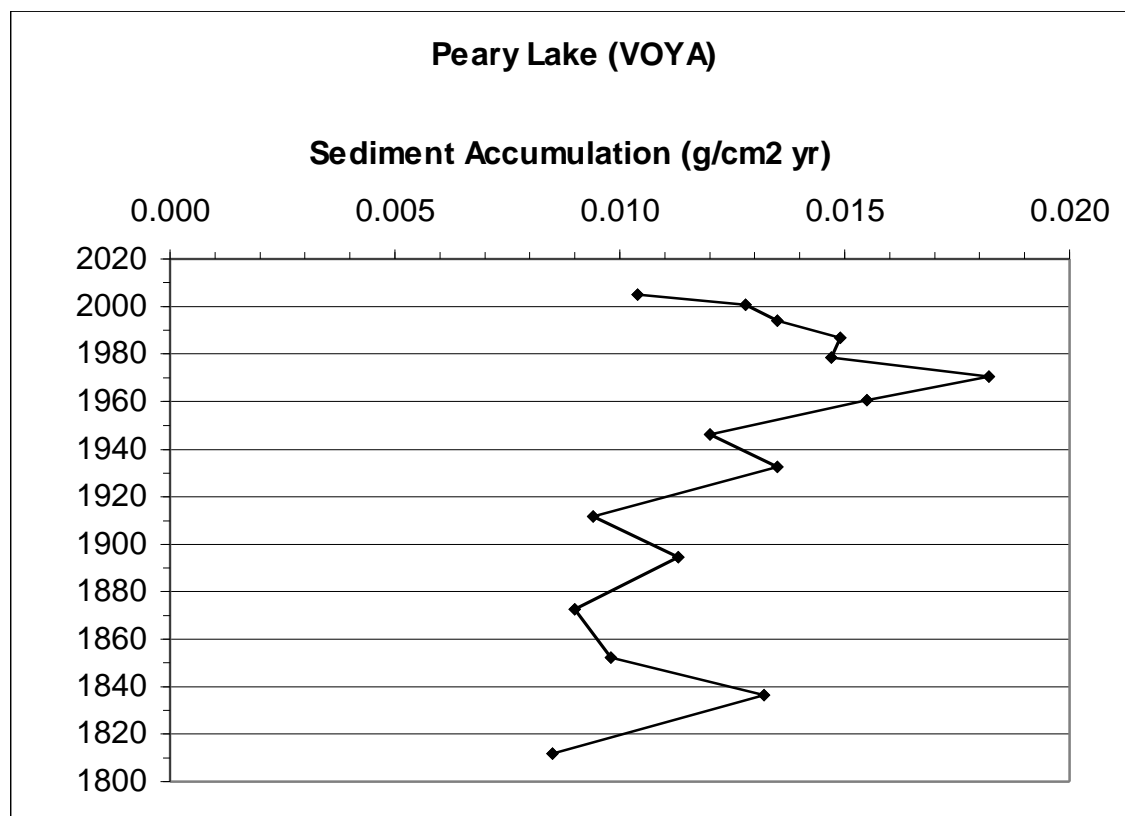
Figure 11. Sediment accumulation rate, Peary Lake (VOYA), g cm^{-2} yr^{-1}.
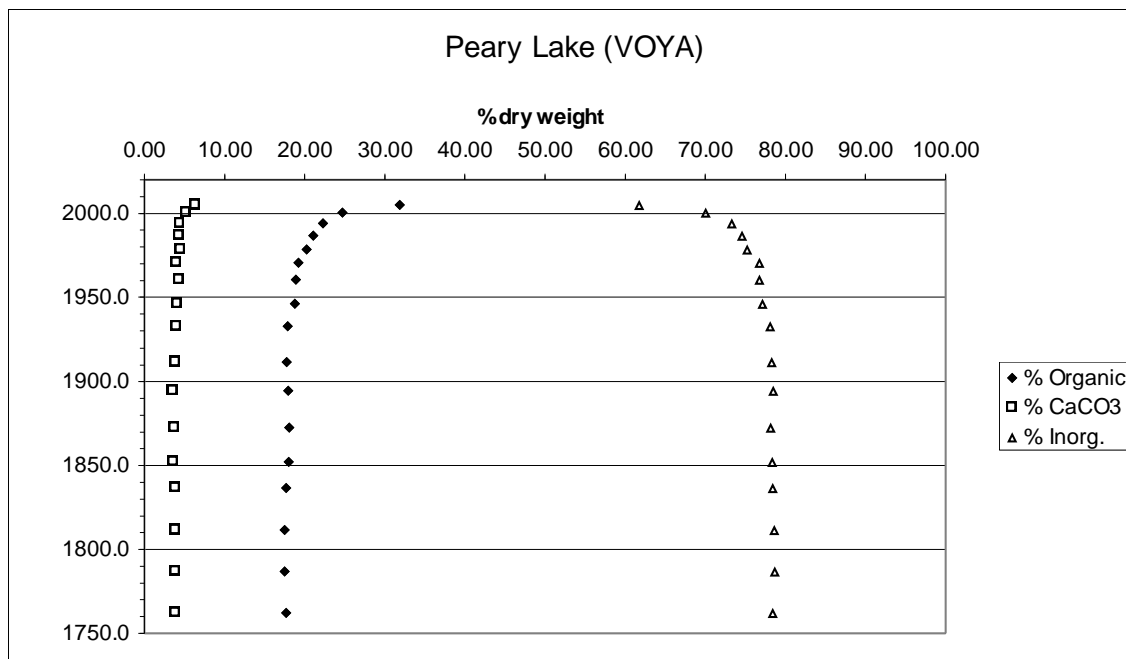
Figure 12. Percent concentration of CaCO$_3$, organic carbon and inorganic matter in Peary Lake (VOYA) core.
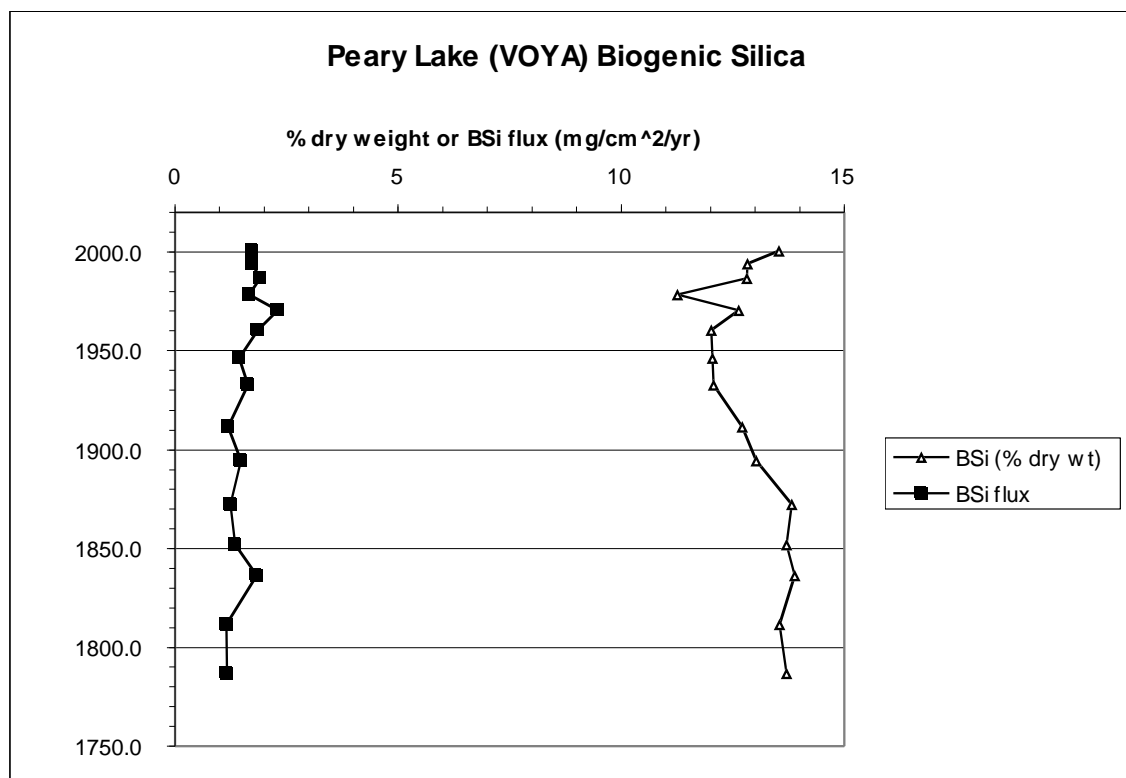
Figure 13. Biogenic silica dry weight percent and flux (mg cm^{-2} yr^{-1}), Peary Lake (VOYA).

34
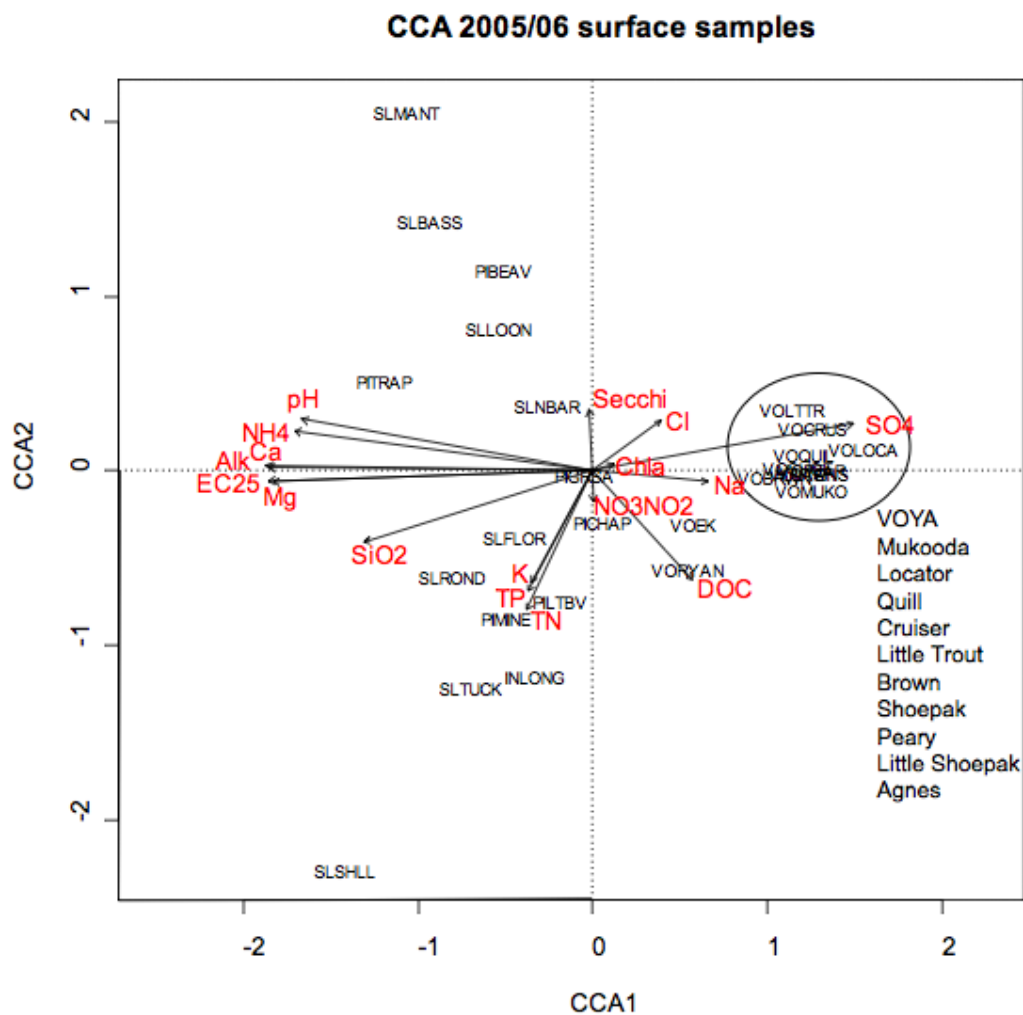
Figure 14a. Canonical correspondence analysis (CCA) of diatom species-environment relationships in SLBE, PIRO, VOYA, and INDU lakes. Environmental vectors and site scores plotted on CCA axes 1 and 2. MISS sites removed from analysis.
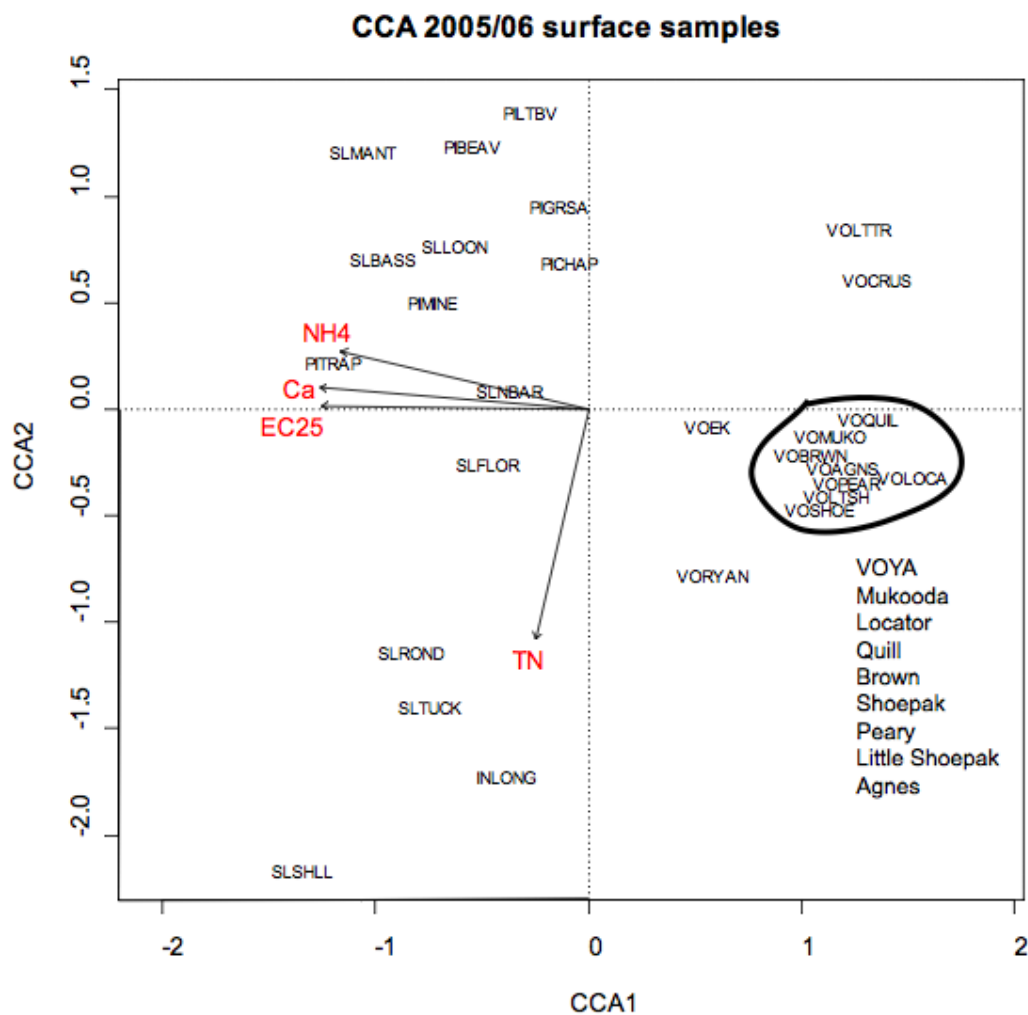
Figure 14b. Canonical correspondence analysis (CCA) of diatom species-environment relationships in SLBE, PIRO, VOYA, and INDU lakes. Environmental variables that explain significant and independent variation in the species data are identified. Site scores plotted on CCA axes 1 and 2.
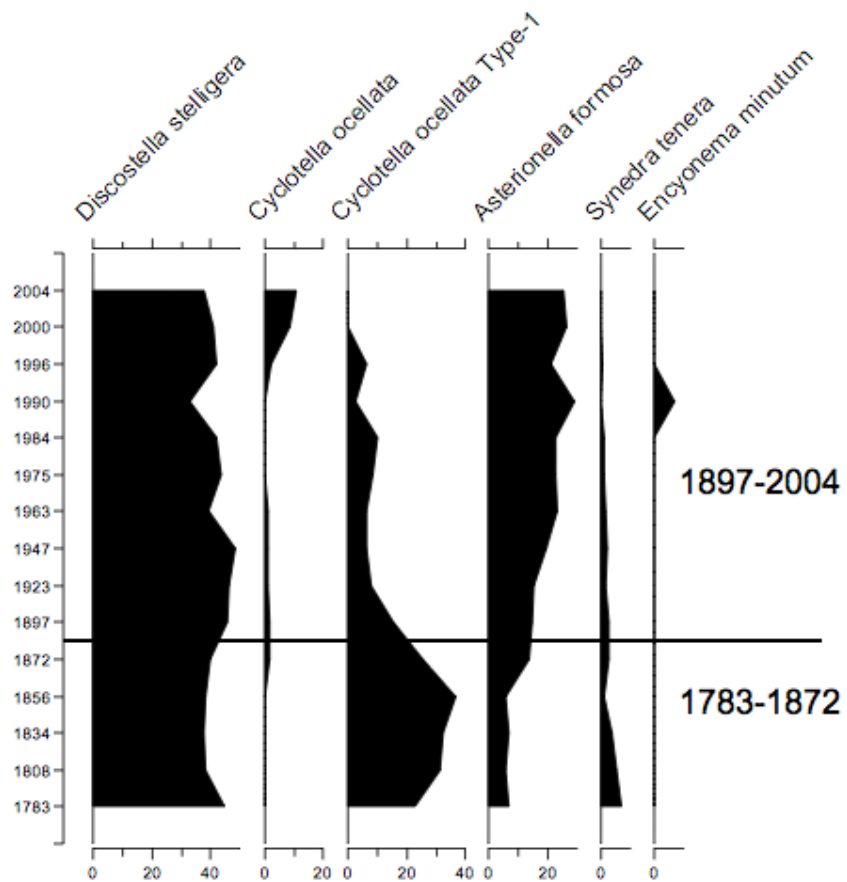
Figure 15. Downcore abundances of taxa found at >5% relative abundance in Cruiser Lake 2006 core (VOYA).
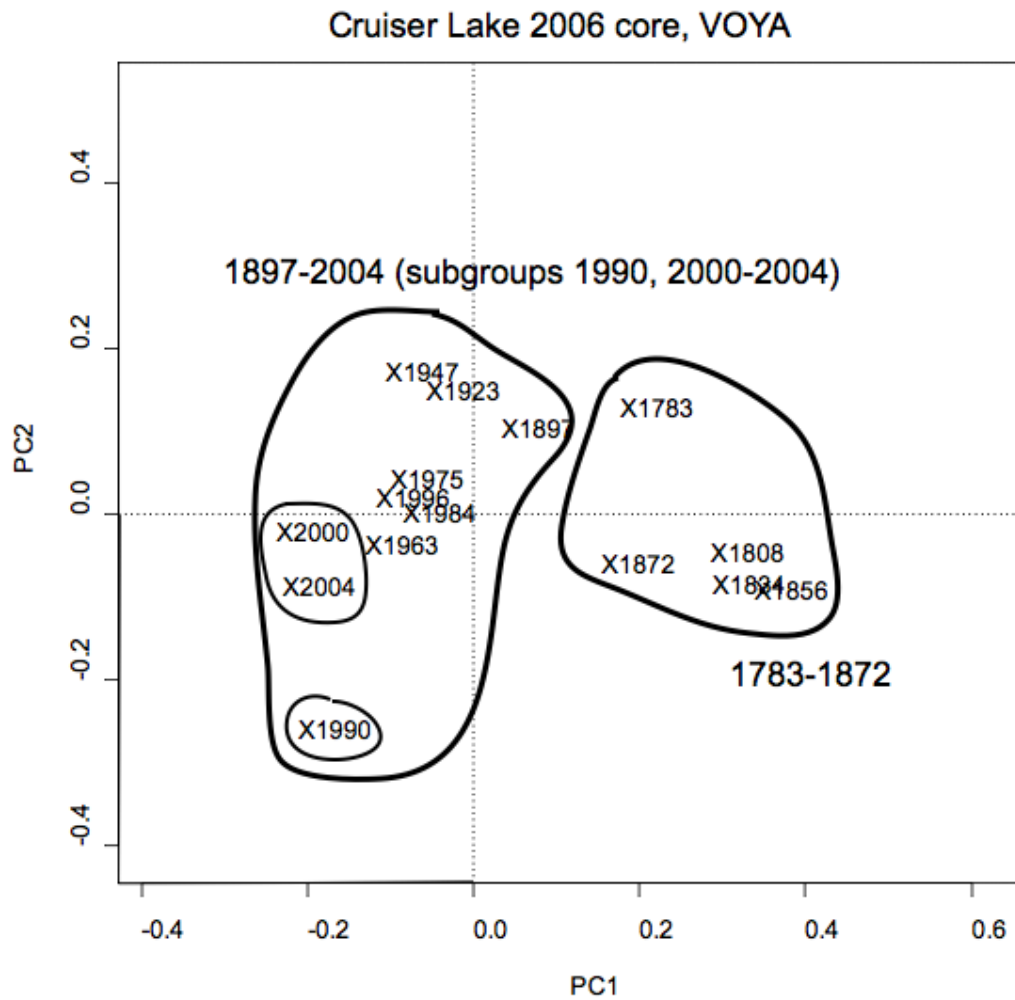
Figure 16. Principal components analysis (PCA) of downcore diatom assemblages from Cruiser
Lake (VOYA, 1783-2004), axes 1 and 2 loadings plotted for core depths.

Ek Lake
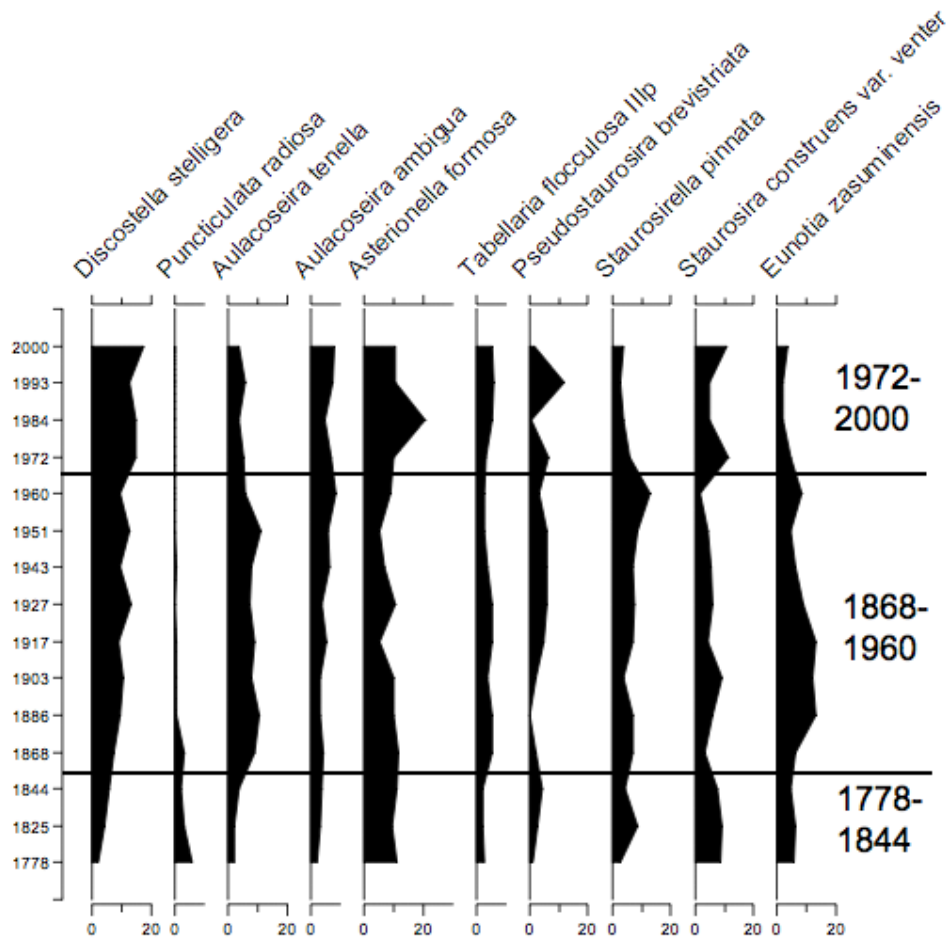
Figure 17. Downcore abundances of taxa found at >5% relative abundance in one or more samples in Ek Lake (VOYA).
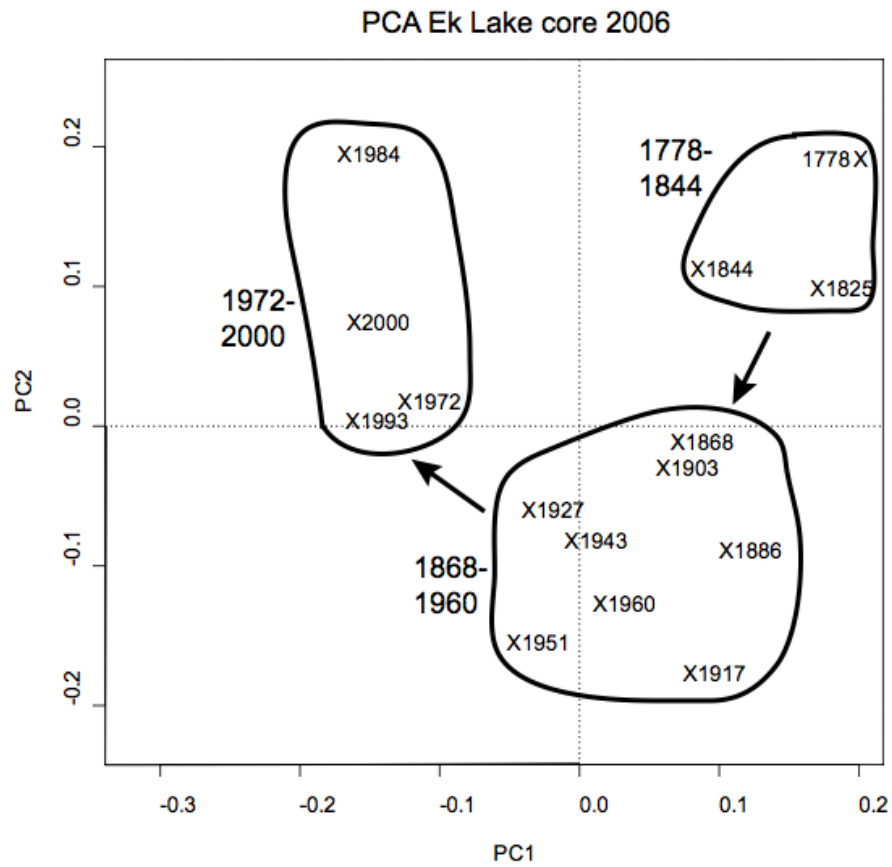
Figure 18. Principal components analysis (PCA) of downcore diatom assemblages from 2006 Ek
    Lake (VOYA, 1778-2000), axes 1 and 2 loadings plotted for core depths.

Peary Lake
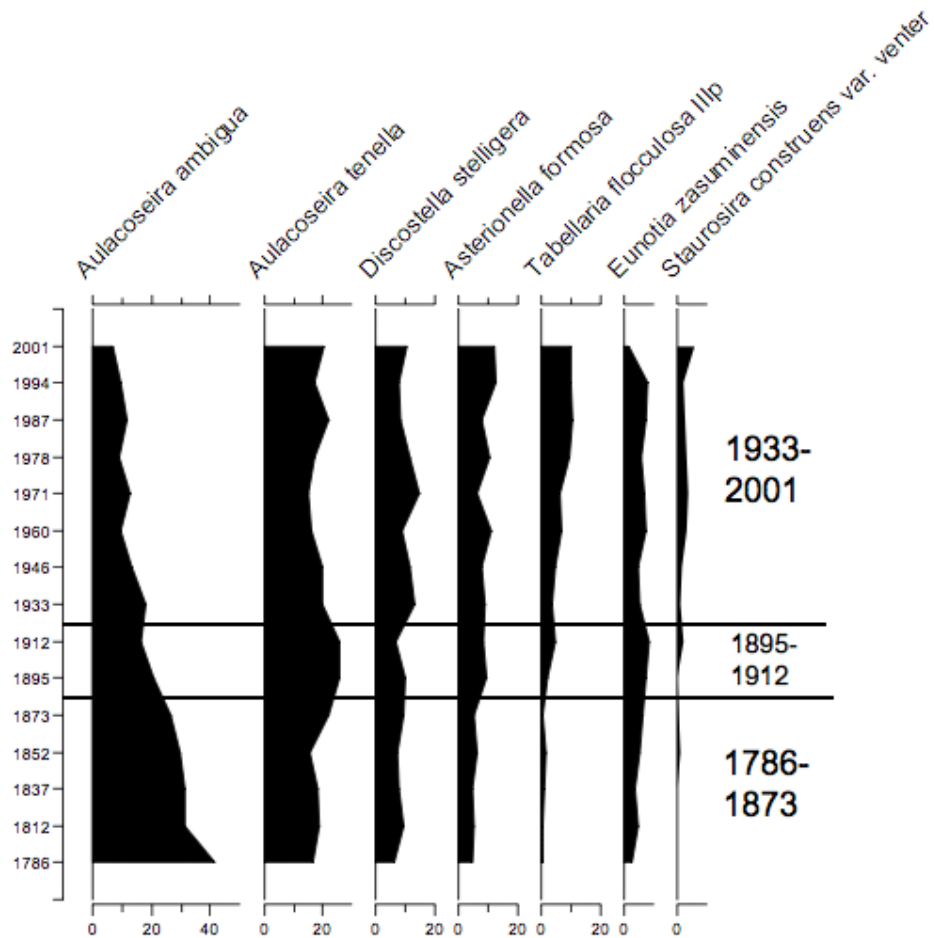
Figure 19. Downcore abundances of taxa found at >5% relative abundance in one or more samples in Peary Lake (VOYA).
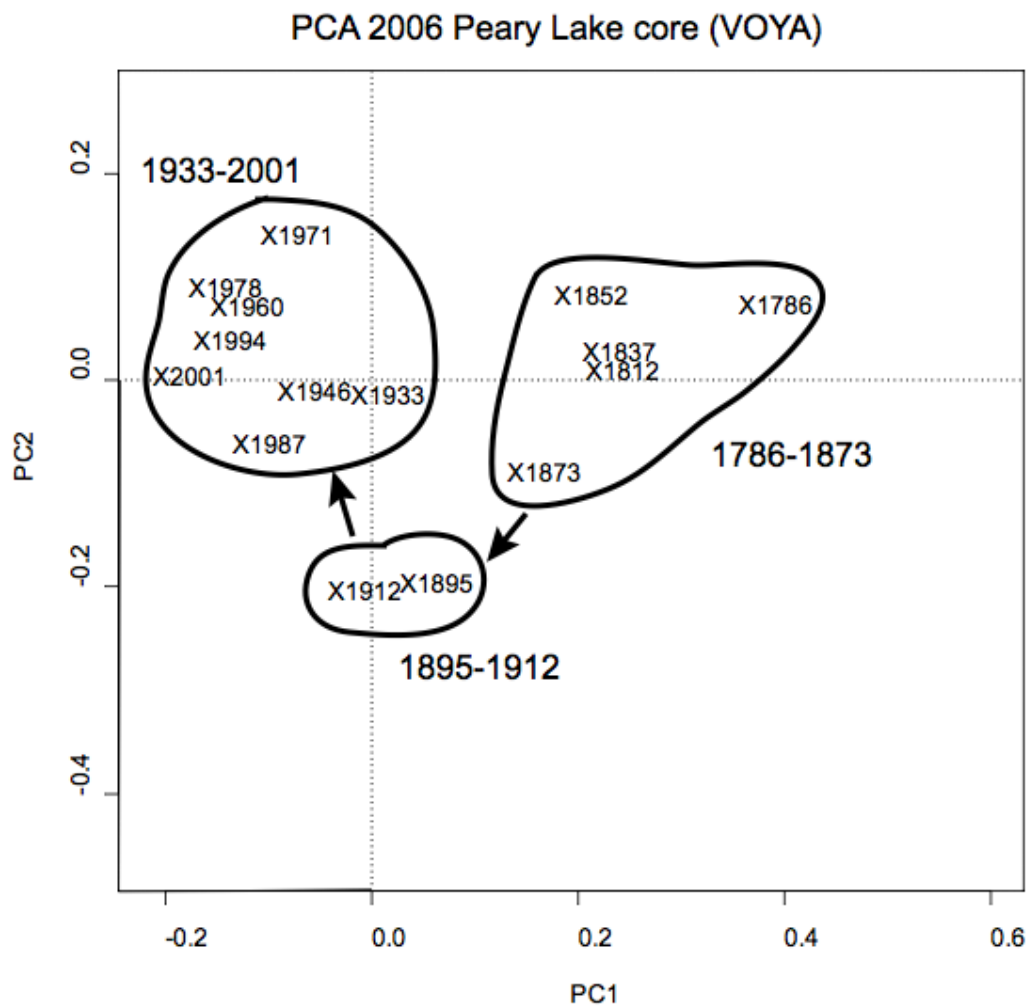
Figure 20. Principal components analysis (PCA) of downcore diatom assemblages from Peary
Lake (VOYA, 1786-2001), axes 1 and 2 loadings plotted for core depths.
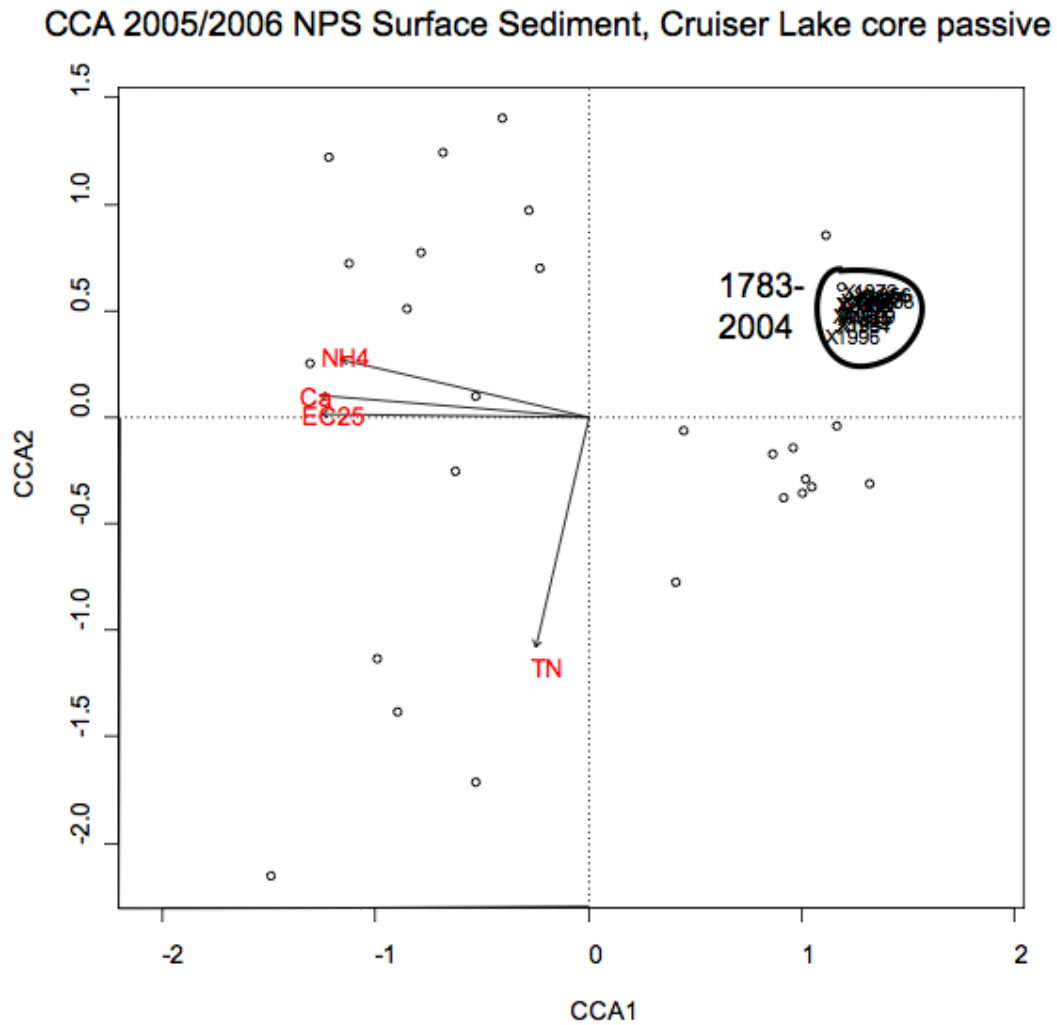
Figure 21. Diatom assemblages from 2006 Cruiser Lake (VOYA) core plotted passively on CCA of diatom species-environment relationships in SLBE, PIRO, VOYA, INDU lakes.
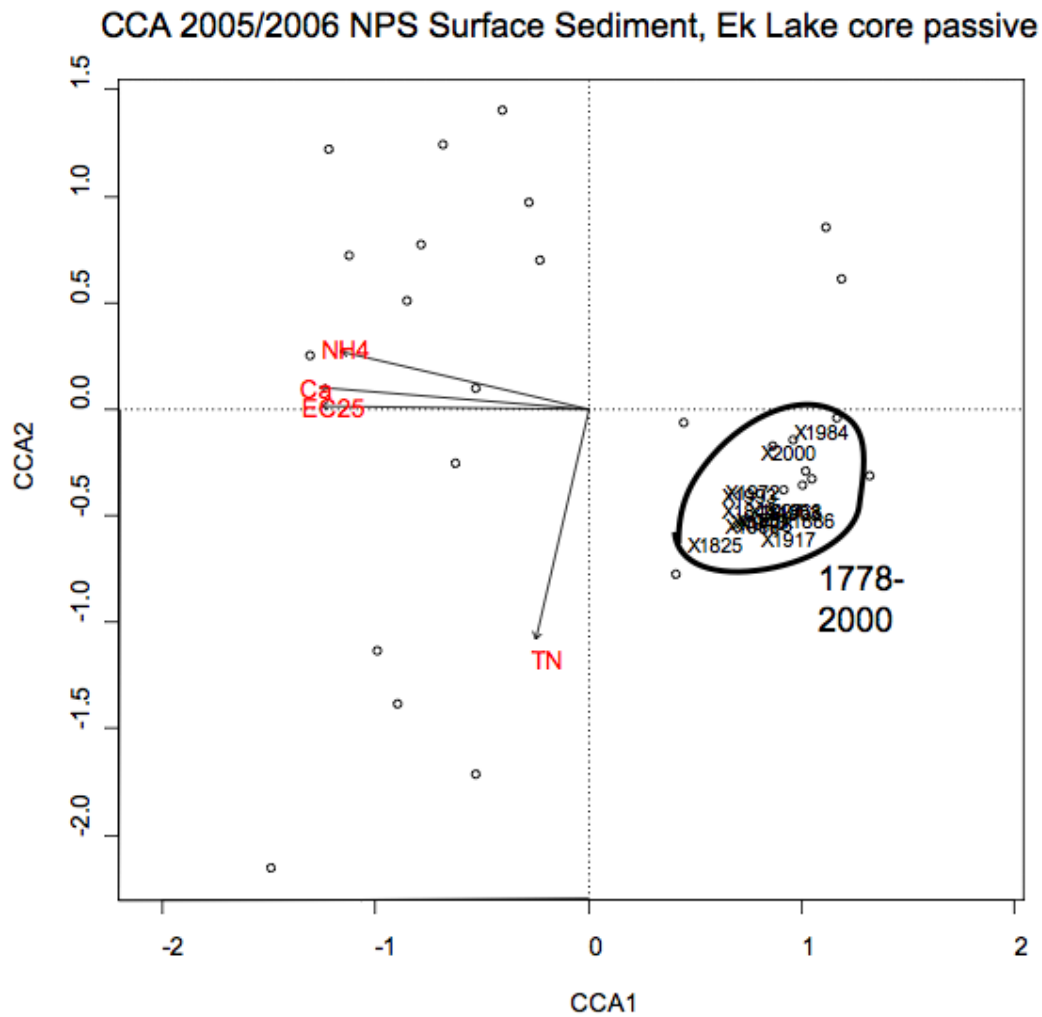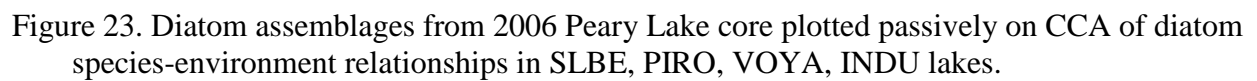
Figure 22. Diatom assemblages from 2006 Ek Lake (VOYA) core plotted passively on CCA of diatom species-environment relationships in SLBE, PIRO, VOYA, INDU lakes.
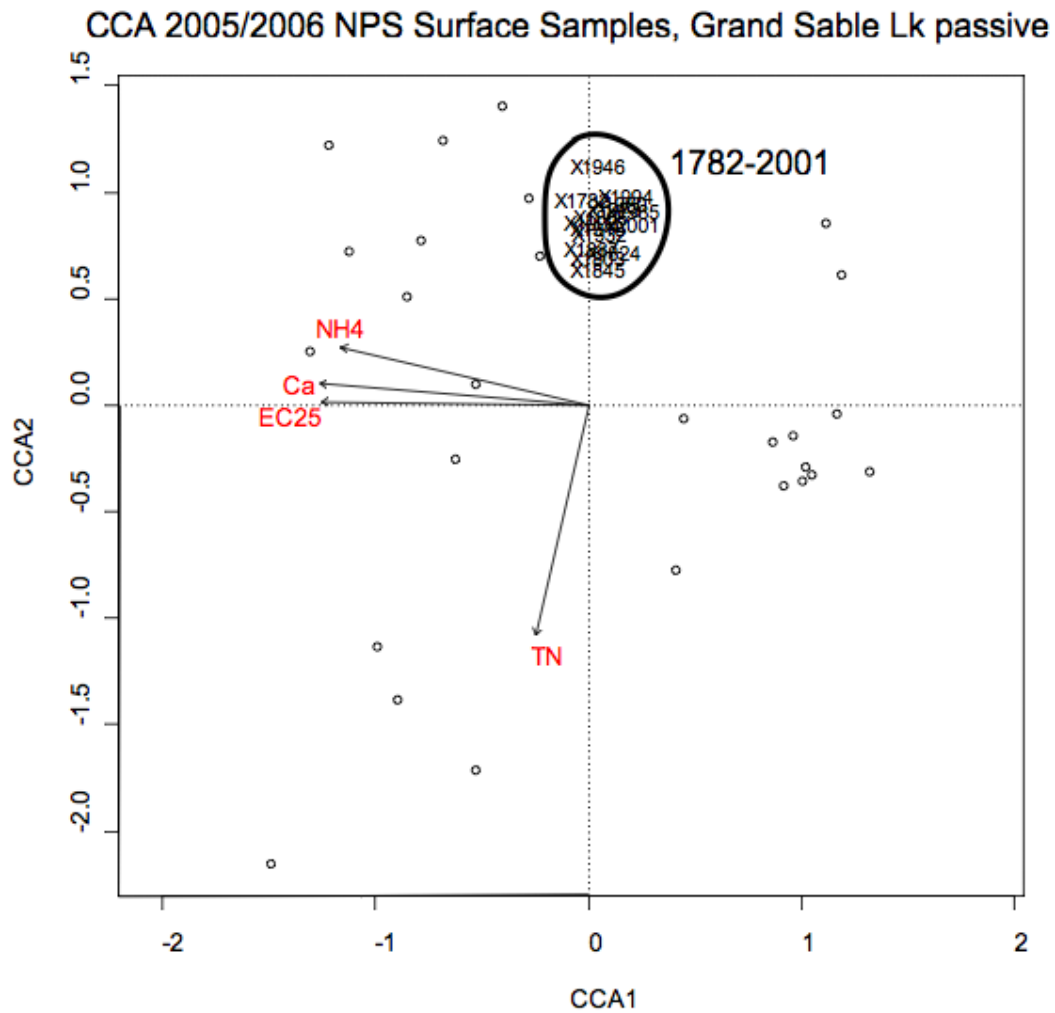
Figure 23. Diatom assemblages from 2006 Peary Lake core plotted passively on CCA of diatom species-environment relationships in SLBE, PIRO, VOYA, INDU lakes.

Figure 24. Diatom assemblages from 2005 Grand Sable Lake core plotted passively on CCA of diatom species-environment relationships in SLBE, PIRO, VOYA, INDU lakes.
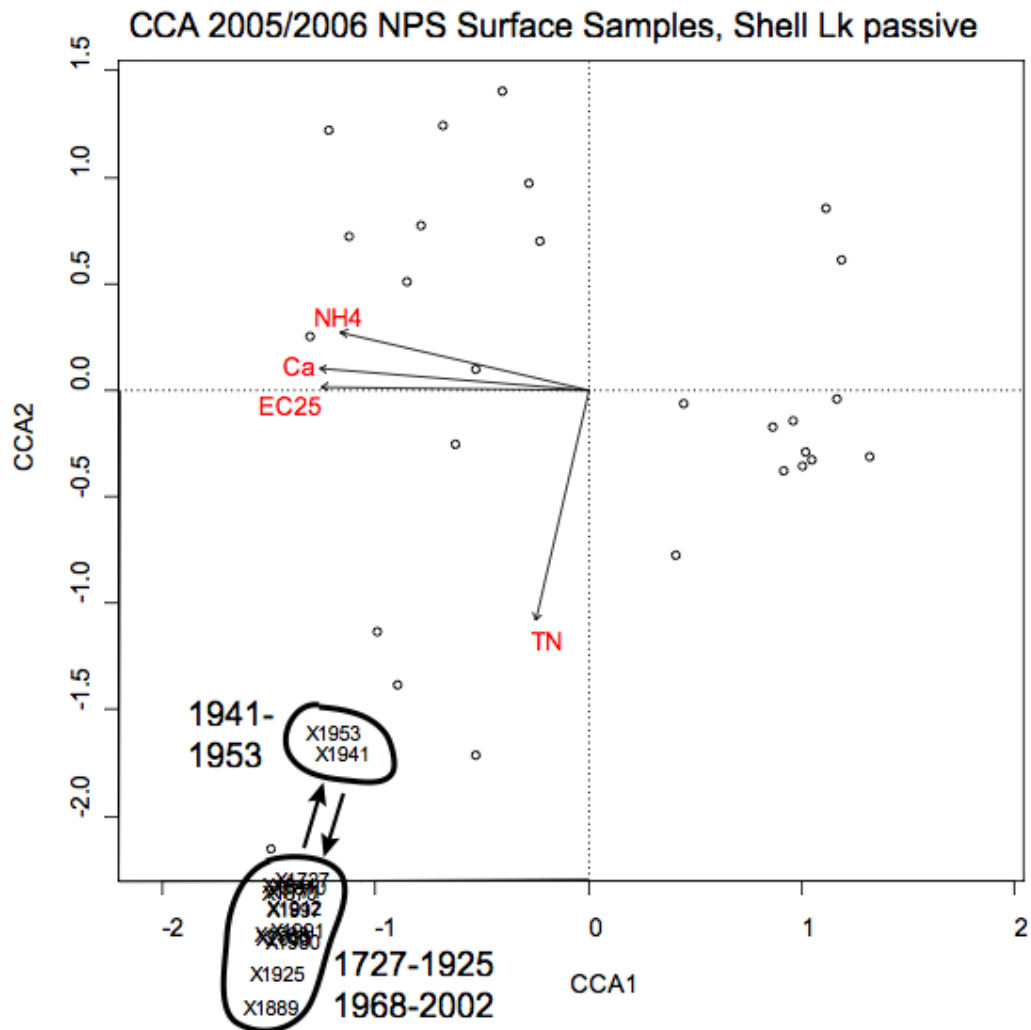
Figure 25. Diatom assemblages from 2005 Shell Lake core plotted passively on CCA of diatom species-environment relationships in SLBE, PIRO, VOYA, INDU lakes.
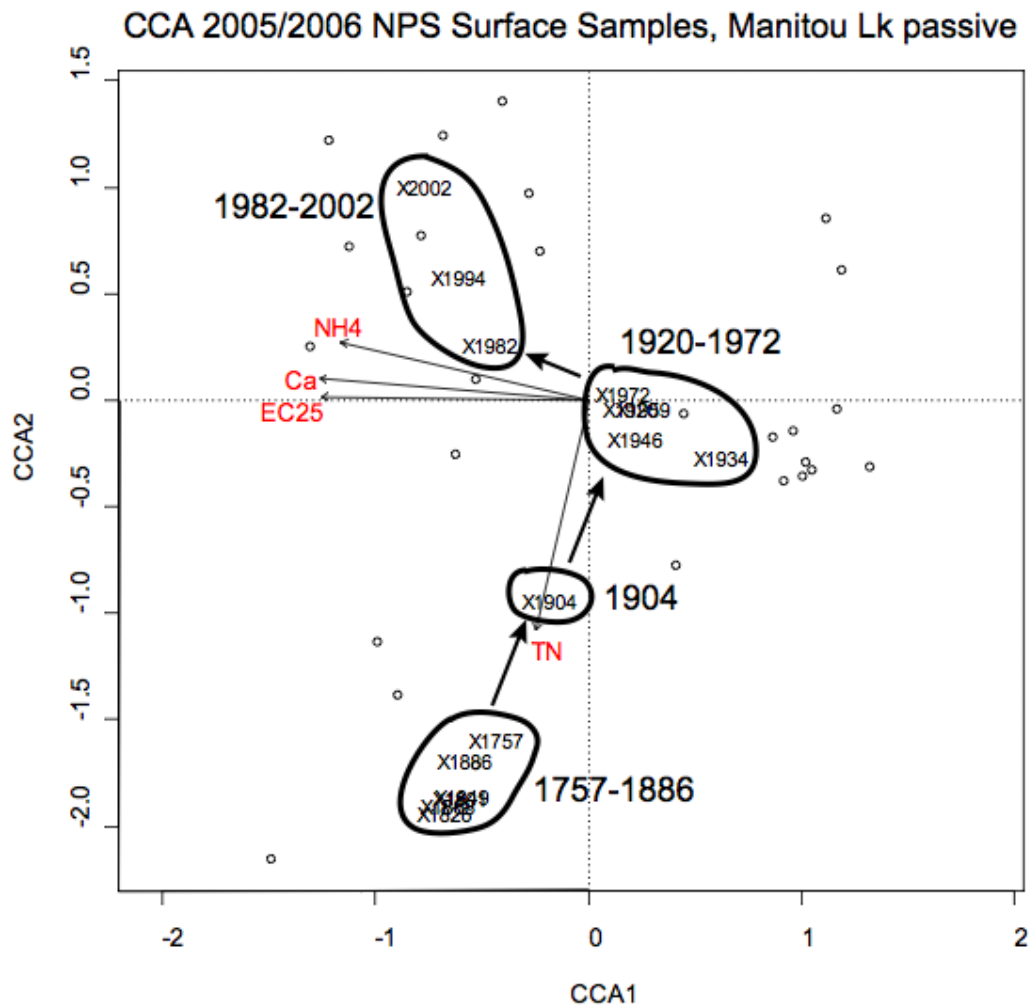
Figure 26. Diatom assemblages from 2005 Manitou Lake core plotted passively on CCA of diatom species-environment relationships in SLBE, PIRO, VOYA, INDU lakes.